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THE MORPHOLOGICAL AND SEDIMENT CHARACTERISTICS
OF THE ELBOW RIVER BASIN

by

C

GRAHAM CHARLES SEAGEL

A THESIS

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ABSTRACT

This study provides information on the distribution of surficial sediments, and morphological characteristics of the Elbow River basin, in order to facilitate future research in this area. Discussion of the evolution and present behaviour of the Elbow River, and notable events concerning the development of the landscape is included.

Sediment samples and morphological information were collected in the field. The results of the laboratory analysis of grain size were analysed statistically using principal component analysis. The morphological information was supplemented by mapping from aerial photographs. Results included a morphological map and a map of the surficial geology.

The conclusions of this study are:

1. Principal component analysis can be used to discriminate between sediment types.
2. Neither antecedence nor superimpositions are conclusively proven to be responsible for discordance between the Elbow River and geological structure in the foothills region of the study area.
3. The distribution of the surficial material is closely related to limits of advance of Cordilleran and Laurentide ice masses.
4. The present Elbow River is in a state of

quasi-equilibrium, due to a decrease in mean annual flow since neo-glacial times which has resulted in a change in the sediment transport characteristics. The result is adjustment of slope in the longitudinal profile to; (a) changes in the amount and size of sediment transported; and (b) the lowering and/or removal of the influence of 'knickpunte'.

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INTRODUCTION

This study concerns aspects of the geomorphology of the Elbow River basin (Fig.1). In particular, the work studies the basin's morphological and sediment characteristics, and analyzes the behaviour of the present Elbow River. The scope of the study is limited in extent and nature by time available for both fieldwork and laboratory analysis. The major objective is to provide a basis for assimilation of earlier, more specific studies and to indicate useful future research.

At this time most of the studies relating to the Elbow River and its basin fall into one of three groups. The first group contains geological studies largely concerned with oil or coal exploitation. The second group of studies involves specific aspects of the hydrology of the basin. The third group of work relates chiefly to the stratigraphy of the area. This latter group usually includes the Elbow basin only in terms of studies centred on the geomorphology of the whole Bow River valley. Specific reference to each of these groups of studies is made below.

The earliest references to the Elbow River are nineteenth century evaluations of the natural history of the area (Dawson, 1885). In the early twentieth century, as mineral exploitation increased, more geologically oriented reports began to appear such as Cairnes (1907), Hume (1928), Slipper

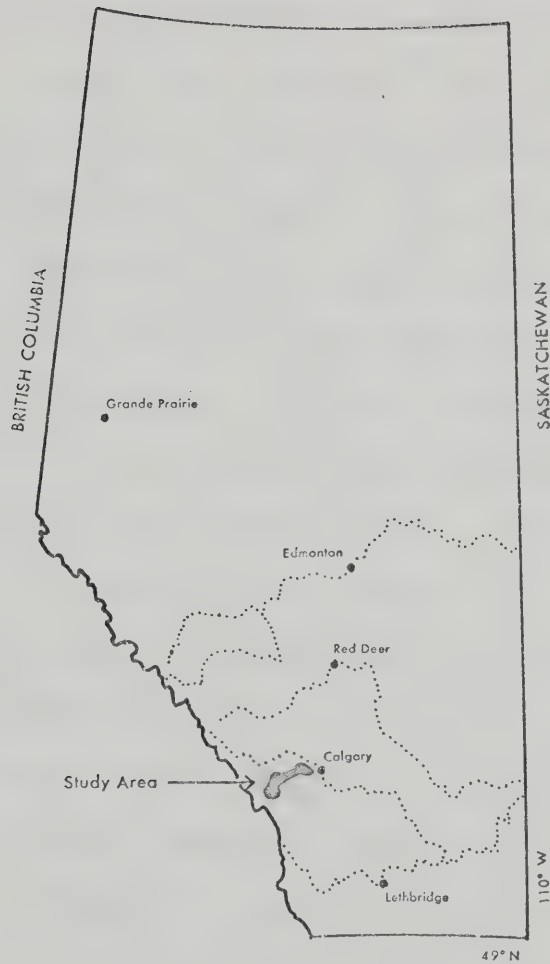


Figure 1

LOCATION OF THE STUDY AREA
WITHIN ALBERTA, CANADA

GCS

(1921). By 1930 more detailed geological studies were carried out by Hume (1930 and 1931). The most complete geological inventory of the area was prepared by Beach (1943) and published by the Geological Survey of Canada.

In 1933 the Glenmore Reservoir (Fig. 2), a dam on the Elbow River which still supplies water and hydro-electric power to the City of Calgary, was constructed. Public awareness of the Elbow River and its behaviour increased; previously only a few individuals who farmed the low, rich, flat land upstream of the reservoir were directly concerned with the hydrology of the river. It is of interest to note that the name of this river was taken from the description the early farmers gave to the channel pattern (Pers. comm., Mr. Murray, Calgary). The erratic behaviour of the river has caused several inquiries, involving cases of individuals who built or farmed on the floodplain and incurred loss or damage of property due to channel changes or flooding (Pers. comm., Mr. A. B. Hollingshead, Research Council of Alberta).

The presence of the reservoir created a need for reliable information concerning flow duration and the source of water. Hence, discharge recording stations have been in operation for over forty years in the basin. In 1961 Meyboom carried out a study on groundwater resources for the City of Calgary. The Elbow River had low groundwater seepage rates and consequently a high runoff fraction of total precipitation. In 1965, Deeprose reported on the Elbow River floods. There are two studies of sediment infill rates for the Glenmore

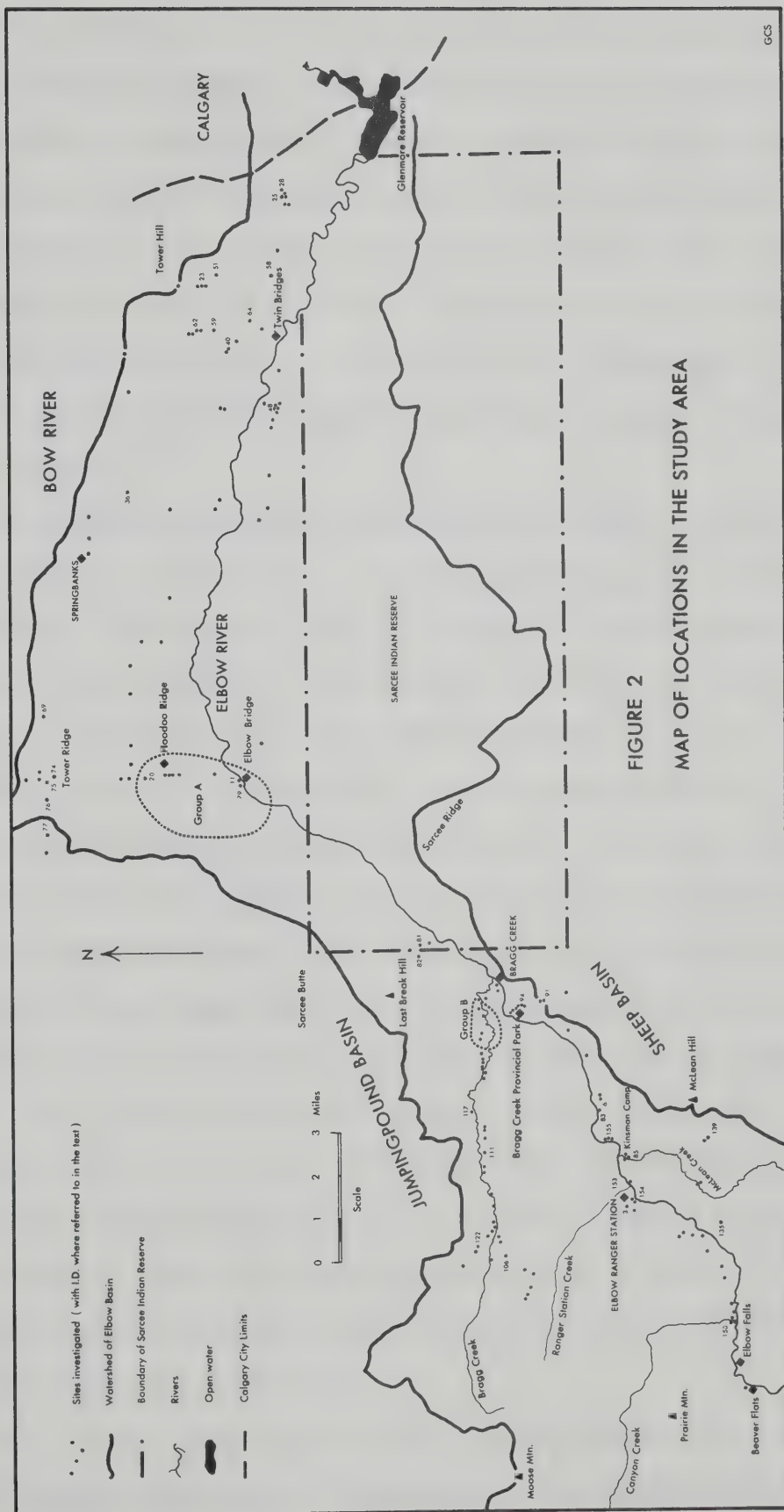


FIGURE 2
MAP OF LOCATIONS IN THE STUDY AREA

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Reservoir by Yaremko and Mustapha (1967), and Hollingshead (1969). Concern regarding the behaviour of the Elbow River and the lack of knowledge of sediment transport rates for the river upstream of the reservoir, led to a study by Hollingshead (1967 and 1968). This study measured bedload as well as suspended load for selected reaches downstream of Bragg Creek discharge station (Fig. 2). This work by Hollingshead (1967) required the building of a third discharge station at Beaver Flats (Fig. 2).

At present the Elbow River basin is used extensively for recreation by Calgarians. This pressure on the area has caused concern about pollution of Calgary's water supply. Because of future possible coal mining activity in the area the Eastern Rockies Forest Conservation Board agreed to undertake a study of the capacity of the Elbow River to carry potential waste products from strip mines. The study was carried out using artificial tracer materials and determined the optimal waste-bearing level that the river could sustain under varying flow conditions. A pilot study had indicated the significance of dispersal of waste as the rising limb of the peak flow curves were developing. (Pers. comm., Mr. W. Poliquin of the E.R.F.C.B.). Finally, the forest rangers are becoming more aware of despoliation of the forestry area caused by modern types of vehicles which have access to previously inaccessible areas and by commercial interests which cause land use conflicts.

The topics studied by others in the Elbow River basin have been highly selective. There exist few comprehensive

studies of the physical environment other than of factors pertaining to the forestry environment. At the same time, as shown above, there appears a need for more general research in the area and especially for research which can be used in the compilation of an inventory of the basic factors of the physical environment.

The detailed studies which refer to the study area are mentioned in the following chapters. The lack of research into the morphological and sediment content of the basin is evident in the general manner in which the Elbow River basin is referred to in much of the literature reviewed.

CHAPTER I

THE STUDY AREA: A DESCRIPTION

The Elbow River is a tributary of the Bow River, with the confluence in the City of Calgary, Alberta. (Fig. 1). The headwaters of the Elbow are in the Rocky Mountains, seventy miles to the southwest of Calgary. The river traverses the eastern ranges of the Rocky Mountains, through both the Alberta foothills and the western edge of the Prairies.

The geological boundary between the Rocky Mountains and the foothills is usually taken as the major thrust separating Palaeozoic from Mesozoic rocks (Beach, 1943). Within the Elbow basin the thrust is found on the eastern flank of Nihahi and Compression Ridges which run NW to SE (Fig. 20). Topographically, the foothills are found to the east of a line running NW to SE through Beaver Flats. This line separates the rugged, glacially denuded landscape to the west from a region of increasing glacial infill to the east. Relief is lower to the east and slopes are less rugged. The tree line is found at an approximate elevation of 7500 feet. As is typical of most of the Rocky Mountains, soils are mainly azonal. In the foothills the soils are chernozems, and the lower relief gives to a heavy forest cover with lodgepole pine grading to the east into poplar. The writer estimates the tree cover to be at least 85 to 90 percent for the foothills portion of the area studied. A few miles east of Bragg

Creek the relief sharply decreases. The lower Elbow basin, east of Last Break Hill (Fig. 2) is a broad grassland area and soils are more characteristically dark black earth in type (Wyatt, Newton and Bowser, 1960). The relief and geology of the whole area are discussed more fully in Chapter Three.

The specific study area (Fig. 2) was limited to the 241 square miles (area taken from basin catchment figures given in Hollingshead, 1968) which is downstream of Beaver Flats. It was felt that this size would give an optimal solution to the two problems of having a large enough area to produce meaningful results at the scale desired and having a fixed amount of time to travel over that area, collect samples, and carry out laboratory analysis.

The methods used in carrying out the study of the sediments and the morphology mentioned in the introduction will now be discussed. Based upon an initial evaluation of the area from aerial photographs maps, and from the study carried out by Hollingshead (1967), two important factors could readily be discerned. The first was the apparent significance of geological control first suggested by Beach (1943). The second factor was the significance of the content of the surficial deposits marginal to the main valley of the Elbow in the assessment of sediments in, or deposited by, the present river. This idea was first suggested to the writer by Mr. Hollingshead (Pers. Comm., 1970). By studying these factors it should be possible to determine adequately the

genesis, morphology, and present day dynamics of sediment distribution in the valley of the Elbow River.

Most of the time devoted to fieldwork was spent collecting samples of the surficial deposits, although observation of morphological characteristics of the landscape was made throughout the area. The latter information was used in the derivation of the major significant morphological interrelations postulated for the area. The compilation of this data necessarily requires study and appreciation of the Pleistocene and post-Pleistocene chronology of events in the area and its hinterland. No attempt is made to establish any absolute chronology for the area, though it is necessary for clarity to place events relative one to another in time. When the surficial sediments are mapped on the basis of samples analysed, it is then possible to interpolate and consider distributions of sediments over the whole area. This enables morphological analysis to be carried out and thereby finally yields clues to the river's behaviour in the past. This behaviour will primarily relate to general channel patterns and to estimates of valley base material and their relationship to the morphology and sediments found.

In carrying out the field and laboratory work, several unexpected events were encountered and it may be of benefit to future workers planning research in this or similar basins to itemize these. A flood of unusual magnitude washed out the bridge near the Elbow Ranger Station and this necessitated collecting more samples downstream of Beaver Flats than had

been originally planned. The existence of the Sarcee Indian Reserve imposed rigid restriction on sample collection in the centre of the study area. Altimeter traverses were considered unreliable because of the rapid daily pressure fluctuations in this foothill region. A final restriction was that the time required to complete laboratory analyses was considerably underestimated, and this aspect of the work was therefore limited to grain size analysis.

Despite these difficulties nearly all of the objectives of the study were met, and although the validity of the conclusions would have been greater in an area without these problems, it is felt that the contributions made by this work are nonetheless worthwhile.

CHAPTER II

GRANULOMETRIC ANALYSIS

This chapter is concerned with sediment sampling, mechanical analysis of samples, and the analysis of the grain size data.

Collection of Samples

Although random sample plans were prepared, the size of the area and the heavy forest cover (Plate 1) forced the rejection of this method. Since sites which could be visited were spatially limited, a pragmatic sampling design was used and samples collected wherever possible. It is felt, therefore, that the number of samples of each sediment type are biased. The number of samples of each sediment type is shown in Table 1. In addition, the irregular and often excessive distance between sample points (see Fig. 2), combined with the scale of variation discovered, in some areas preclude reliable interpolation.

The final sample pattern (Fig. 2) reflects the access routes in the basin and emphasizes the main valley base area. Notable unsampled areas are the Sarcee Indian Reserve and the inaccessible area upstream of Beaver Flats.

At each site samples were taken as far below the surface as possible to avoid suspected periglacial interference and to minimize the effects of weathering. Periglacial action

Prairie Mt.

Moose Mt.

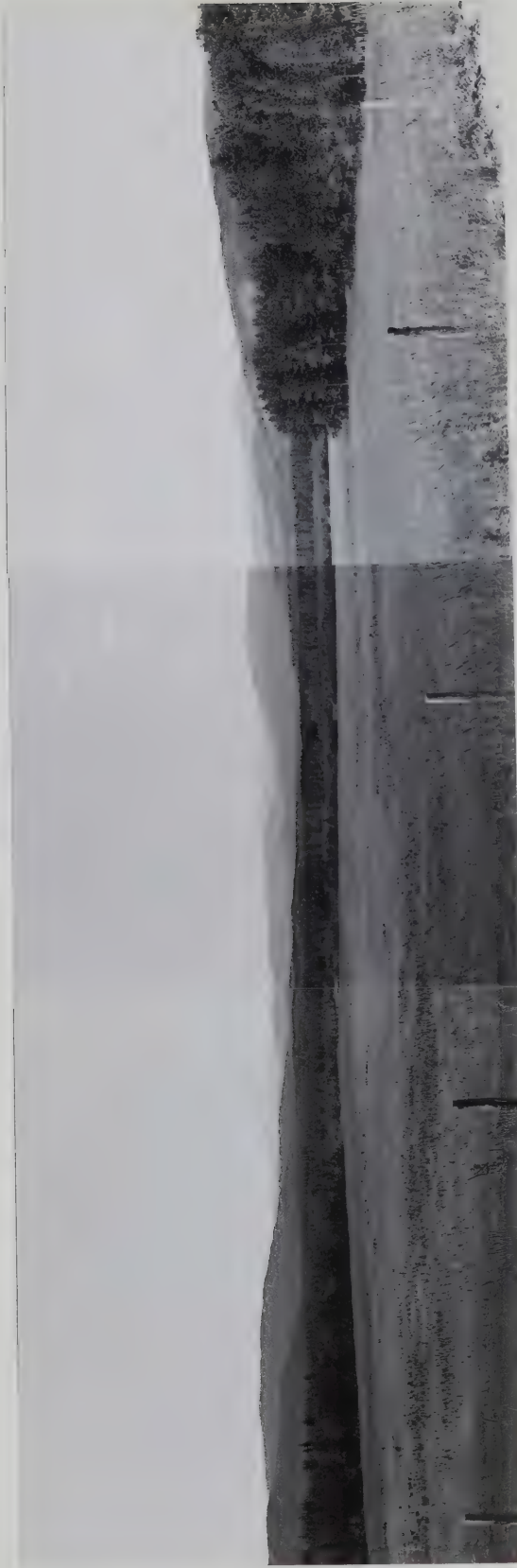


PLATE 1

View west from the Kinsman Camp; Note the heavy forest cover masking the Elbow River valley in the immediate centre foreground. The foreground is the area between the Elbow Ranger Station and the Kinsman Camp, with McLean Creek entering from the left of centre of the photograph.

TABLE 1
NUMBER AND TYPES OF SEDIMENTS
COLLECTED IN THE FIELD

Total number of sites	155
Samples collected (Based on subjective field allocation)	
Cordilleran Till	45
Laurentide Till	37
Coarse Fluvial Gravels	61
Deltaic Deposits	6
Fine Grained Fluvial Sediments	16
Ash	8
Lacustrine	93
Total	268

is evident in the form of ice wedge pseudomorphs and contortions of sediments in which the structure is apparent from the homogeneity of the grain size contents and colour within each contortion. Sampling from such structures would not be representative of the sediment type. A further precaution included the omitting of exposures at road cut locations where the road side of the cut was banked (fig. 3). This was because of the common practice of highway engineers of ploughing overburden into the cut from the cut side to produce the bank.

At sites where suites of different sediments were found, samples were taken of each of the clearly discernable types.

The size of the sample taken from each sediment type at each site was in the range 500 to 1000 grams. In the case of sediments thought to be till, the sample was taken in such a way as to avoid pebbles greater than 32mm. This was because the size of sample required to generate statistically feasible results for the grain size content precluded such an undertaking in this study. The coarse fluvial samples in which boulders greater than 256 or even 512mm in diameter occurred, regularly necessitated larger samples being taken and the use of a different procedure for collection in the field. The samples taken for laboratory analysis were in the range 5000 to 10,000 grams and sieved for material less than 32mm. The coarse fraction was measured from photographs which were taken of each coarse fluvial samples (Plate 2) using a plastic one-foot ruler for scale. A correction factor could have been applied had it become necessary to distinguish

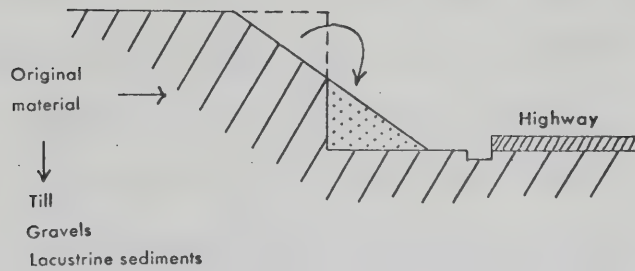


Figure 3

Section through road cut to show clear portion for sampling

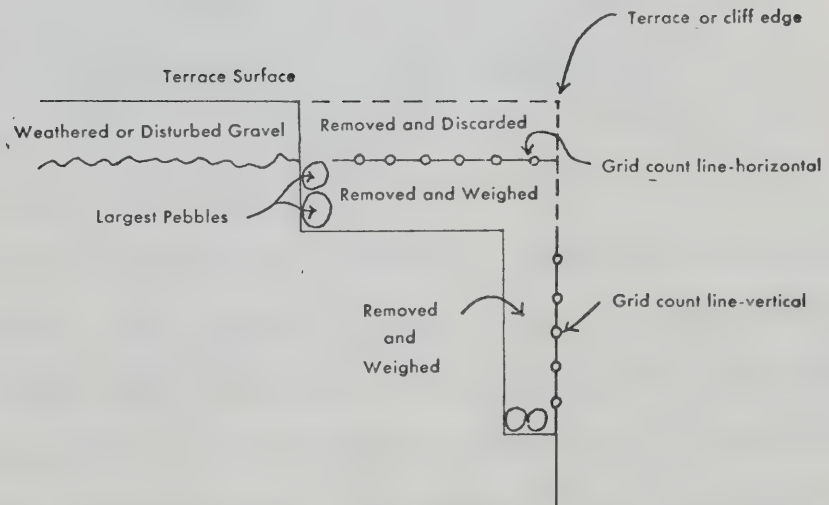


Figure 4

Sketch of positional procedure used in the bulk field sieving of gravels

between different types of coarse gravel. The sites (numbers 83 and 3, shown in figure 2) for which the analysis was completed were chosen such that the procedure could be applied to both the horizontal and vertical sections (Fig. 4.).

At each site the top soil was cleared away completely. Then a hole was dug to a depth of twice the length of the A axis of the largest pebble. The hole was square and the length of each side was four times the A axis. This procedure was devised by Kellerhals and Bray (1970) to ensure that the largest pebble contributed less than three percent of the total sample weight. The material removed was sieved in the field through 8, 16, 32, 64 and 128mm sieves. The base of the hole was levelled and cleared with a soft brush. A grid with 100 intersections each 50mm apart was placed over the cleared surface and photographed (Plate 3). Finally, the pebbles from underneath each intersection were removed and the A, B and C axes measured. Material less than 8mm was designated fines. The problem of more than two intersections on the same pebble was solved by re-locating using randomly selected coordinates. This was done only once for each such situation. This procedure was the same in the horizontal and vertical case except that in the former, gravels less the 1/2" deep were not counted and the underlying pebble measured instead. This was done because of the difficulty of arriving at an undisturbed and clear surface on the horizontal.

Mechanical Analysis of Grain Size

The laboratory analysis was preceded by a grouping

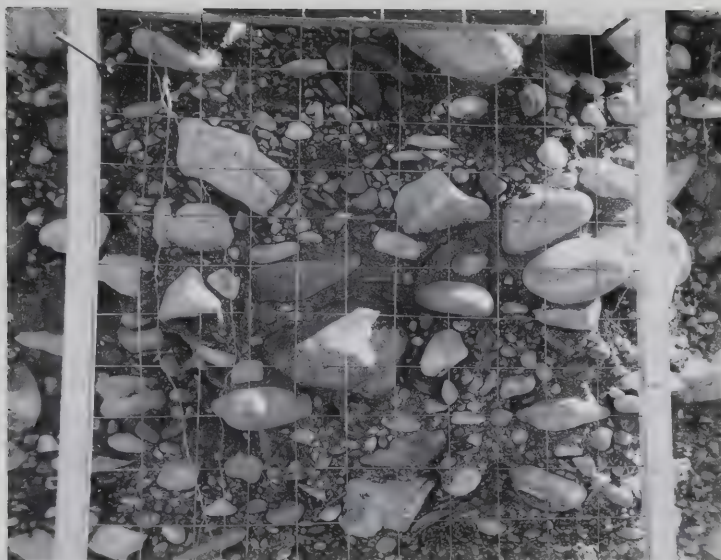


PLATE 3

Shows a grid with 100 intersections, each 50 mm. apart, in a vertical gravel section.

of the samples to facilitate a more efficient granulometric study. The ash samples, initially determined by their surface location at each site and their distinctive orange or yellow colour, were analysed mineralogically under the microscope with the assistance of Dr. J. Westgate of the Geology Department at the University of Alberta. The conclusion was that the ash samples were clearly identifiable and need not be further analysed (Westgate and Dreimanis, 1967; Smith and Westgate, 1969).

The remaining seven groups were sieved. The procedure used in the laboratory is given in the flow diagrams of figures 5 for the fines, and 6 for the coarse fluvial and deltaic samples. The two procedures were used since the coarse fluvial and deltaic sediments were already clearly distinguishable on the basis of pebble size, bedding structures, pebble shape and morphological form. The procedure for all other samples was designed to allow statistical comparability between each group. Hence, sieving was cut off at the upper and lower limits of 8mm and 0.063mm respectively. The presence of 82 samples of at least two till types created the need for the upper limit. The distinctiveness of the coarser than 8mm fraction could only be truly ascertained by field sieving of very large samples. The lower limit was imposed because of a shortage of time for the pipette analysis of so many samples.

The laboratory sieving of samples was carried out at half phi intervals.

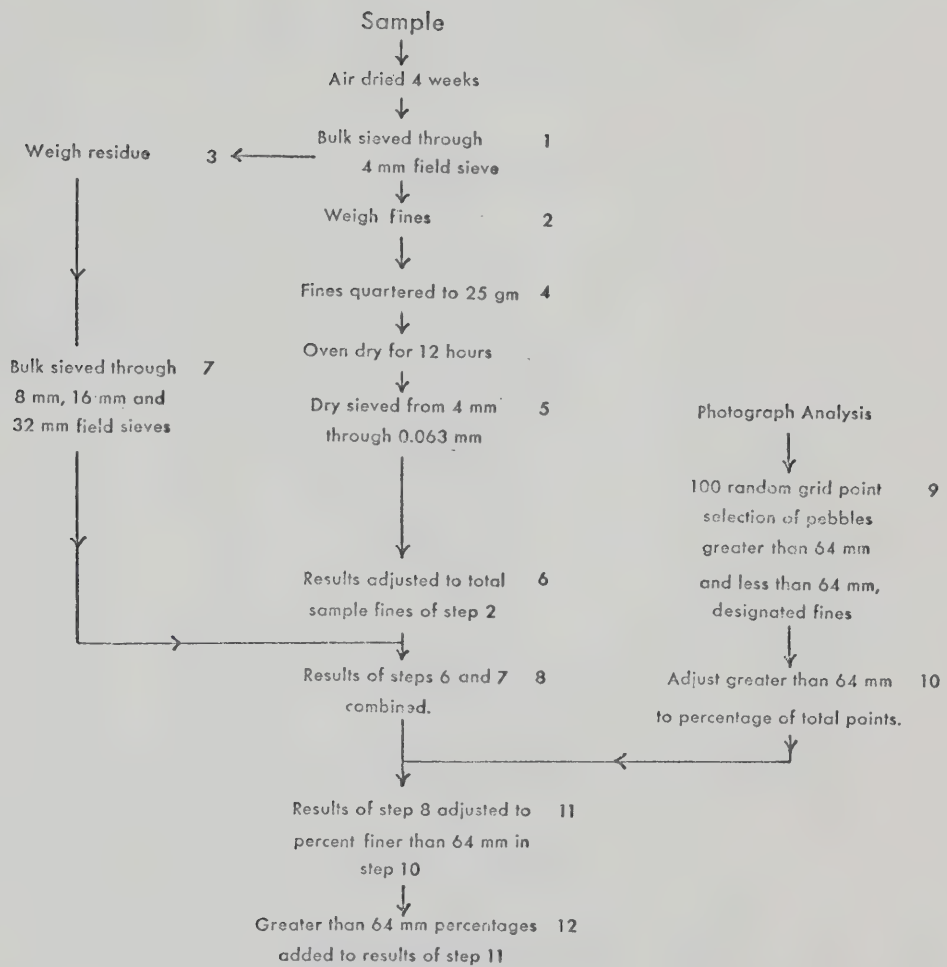


FIGURE 5

FLOW DIAGRAM FOR LABORATORY ANALYSIS OF GRAIN SIZE

COARSE FLUVIAL SAMPLES

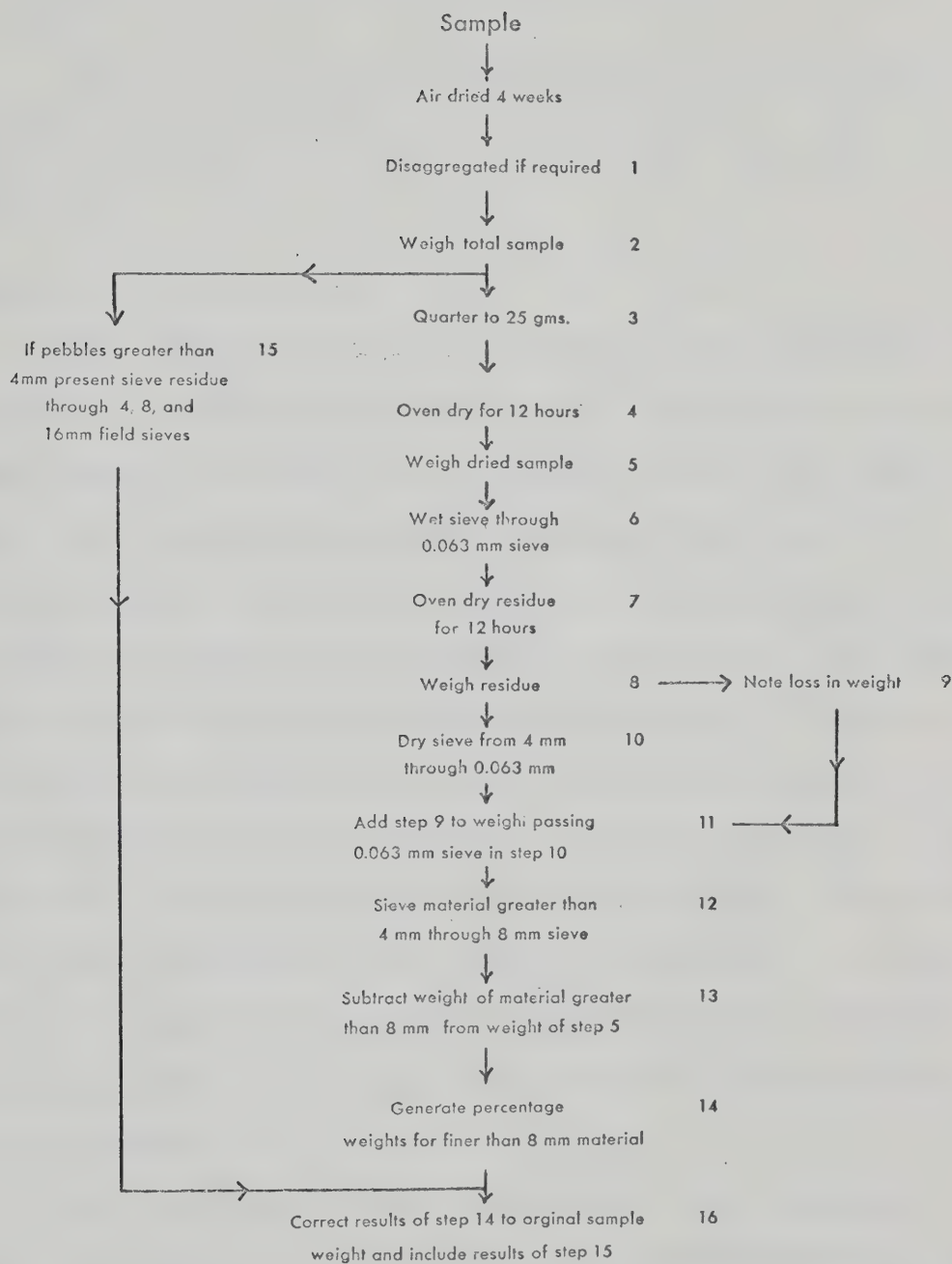


FIGURE 6

FLOW DIAGRAM FOR LABORATORY ANALYSES OF GRAIN SIZE

Analysis of Grain Size Data

This section is considered as an experiment and is presented under the headings of theory, method, results and conclusions.

Theory

The identification of a sediment sample in terms of its mode of genesis is frequently based on several measured properties of the sample; for instance grain size, petrographic and mineralogic content, pebble orientation and locational data. At present there is an increasing awareness of a need for information concerning the spatial and temporal distribution of any one of these properties of a sediment. The problem of characterizing a sediment in terms of genesis and distribution are complex when only one of the properties are considered. This is true of grain size classes, since this is the basic component of all clastic sediments. In this study grain size is the primary property of each sediment sample collected. This property is used to characterize sediment types.

In granulometric analysis there is an increasing amount of information concerning the characteristics of grain size distributions for sediments of various genetic origins. Krumbein (1938) has pointed out that grain size analysis is largely a problem of statistics. It is not surprising therefore, that most granulometric analyses presently undertaken by geologists and geomorphologists are based on the most reliable statistical analysis evolved primarily for such work.

These techniques are referred to as (1) moment measures and (2) graphic statistics. These statistics have been widely discussed by such workers as Sahu (1964), Link (1966), Shepard and Young (1961), Greenwood (1969), Freidman (1961, 1962), Landim and Frakes (1968), Folk and Ward (1957), McCammon (1962) and Inman (1952). Folk and Ward (1957) have developed graphic statistics for grain size analysis to a point where most workers now recognize the technique as reliable as moment measures (McCammon, 1962; and Middleton, 1962). The graphic statistics have the advantages of ease of computation and their visual graphic properties.

The graphic statistics of Folk and Ward (1957) are based on a distribution approximating a logarithmic-probability distribution (Krumbein, 1937; Freidman, 1962; Middleton, 1962). The most characteristic divergence from this relationship, has given rise to what is considered a basic phenomenon of the grain size distribution, namely the curve away from the straight line at each extreme of the distribution (Tanner, 1958). Because of this, one prerequisite of this analysis is that less than five percent of the individual sample weight is included in the smallest and largest sieve class. This graphic analysis which generates mean standard deviation, skewness and kurtosis, is based on percentiles. This means that knowledge of the complete range of grain size classes in the sediment is necessary. Therefore, when there is doubt concerning the whole range of grain size classes (an incomplete data record) or the smallest measured sieve size

represents greater than five percent of the individual sample weight, this form of analysis is not justified. In this case another form of analysis is required.

The descriptive elements generated by graphic statistics are presently being used to identify and discriminate between sediment types (Freidman, 1961; Shepard and Young, 1961). The basis for this work was outlined by Folk and Ward (1957) who wrote:

"Once a relationship is established in an ideal case, where the changes are laid out before the observer in their most perfect form, one soon learns to recognise the same relationships in less ideal examples, where the changes are obscure. The obscure examples, hitherto unfathomable, are explained in the light provided by the ideal examples."

This suggests a two phase operation. The first phase is to deduce certain explanatory facts which distinguish between sediment types in the ideal case. The second phase is the induction from these explanatory facts for the obscure case in order to produce the same discrimination. Hence, when the four elements (or dimensions) of graphic statistics are available, this approach to sediment discrimination may be used for samples from a particular area (the obscure case), and tested against the known results for the same analysis published by other workers (the ideal case). The discrimination considered above is based on uniformitarianism concerning genesis of a sediment. The assumption is that one sediment type is, more or less, similar in grain size content to another. Yet grain size is but one variable which may be used to partially describe a sediment. Therefore, an implicit

assumption of the above is that all variables other than grain size act in the same way for a given sediment type, and that the degree of dependence of grain size on all other variables is the same at all times. Greenwood (1969) pointed out that:

"If a meaningful uniformitarianism can be accepted any likely errors focus, at least in part, on the complexity of the situation and the great number of variables involved. The unrestricted use of any single variable as a criterion for environment discrimination is often suspect because of its possible interaction with a number of other variables. The problem of discriminating between sedimentary environments on the basis of measurable sediment parameters resolves itself, therefore, into an application of multivariate statistics."

The most unique property of the grain size variable is that it may be used to describe any sediment. It is to be expected, therefore, that grain size content is commonly used to reflect the behaviour of other groups of variables than any other single variable. The unknown factor is the degree of influence of the 'other variables'. The implicit assumption of Greenwood (1969) is that variance in the grain size distribution when measured by grain size classes will be manifest in the differences between each grain size class for sediments of different genesis. By analysing these differences using the multivariate statistic of linear discriminate analysis, Greenwood (1969) established that:

"Multivariate discriminate analysis procedures can provide a predictive model for environment discrimination using sediment parameters. Samples of unknown origin can be classified with a defined probability of misclassification."

Problems Encountered in the Analysis

In this study a large number of sediment samples were

collected from a variety of sediment types. The first problem was to verify the original diagnosis of sediment type allocated to each sample collected on the basis of contents, morphological form and location. The second problem was created by the limited time available for laboratory analysis, and involved finding an alternative statistical procedure for analysing and discriminating between samples of different sediment types.

The incomplete range of data for each grain size curve precluded the use of graphic statistics and moment measures. However, since a constant range of grain size classes was used in the mechanical analysis for each sample, a basis for the use of a multivariate statistic had been provided. Greenwood (1969) applied linear discriminate analysis to the four moment measures frequently used to describe the grain size curve. Greenwood (1969) used these four variables as a means of reducing the original number of variables (the grain size classes). However, it was pointed out by the same writer that principal component and factor analysis could be used for the same purpose. Greenwood pointed out that the problem of factor analysis is in the interpretation of the new variables which may well distinguish between the different sedimentary environments, but prove difficult to interpret in terms of their geological significance.

Within the vast field of linear algebra and group theory, Gould (1969) has illustrated the potential use of eigenvalues and eigenvectors in the multivariate classificatory problem. Gould (1969) also points out the usefulness of

principal components analysis in the context of the matrix properties of eigenvalues. In addition, he points out that the parameter being used may have a multi-dimensional character so that the classification cannot be established on one scale. The taxonomic properties of principal components were illustrated by Kendall (1939) for crop productivity in England. The problem of spatial uniformity and/or continuity of a parameter is much reduced when the taxonomic theory applied to a parameter yields a single scale upon which the classification is based. Gould (1969) suggests that principal components is far more powerful than ratio, interval, binary or ordinal scales, and may therefore be considered potentially far more useful when a multi-dimensional, spatial, temporal and multivariate classificatory problem is encountered.

In this study the major problem is classificatory; the data multi-dimensional and sensitive to multivariate dependences, and dependent upon spatial and temporal aspects. It was felt therefore that principal component analysis was the most appropriate statistical procedure to use in order to verify the original sediment sample identification.

The author is unaware of a previous application of this technique to grain size data. Therefore, the analysis using principal components is presented as an experiment, in which the behaviour of each sample and the clusters of samples in each component of a particular sediment type are investigated.

Method

The analysis was applied to Cordilleran till, Laurentide till, lacustrine, fluvial sands, and ice wedge material, all samples of which had been sieved within the same range of 0.063mm to 8mm.

The calculation of percentage and cumulative percentage weights as well as the plotting of this data was programmed for the computer by the author (see appendix 1 for program listing). The plots of the data were made in phi units to a linear scale (a semi-logarithmic plot). In addition, the cumulative percentage curve was plotted a second time with phi units against the logarithm of the cumulative percentage (2 x logarithm plot). Figure 7 shows samples of the plots.

To differentiate quantitatively between the five groups consider the data as a matrix (MO-1) of rows of observations, and columns of the percentage contribution of each of fifteen grain size classes to the sample population. Then the method is to test the significance of the percentages less than 0.063mm for each sample against the original diagnosis of sediment type. Secondly, the latent roots, or eigenvalues of the matrix (MO-1) are generated. Finally, the component listings of the factor loadings are checked for clusters of the five original sediment types, and the existence of any new sediment groups.

Step 1

The first step is to simplify the matrix (MO-1) so that description of each sample is made easier. This is

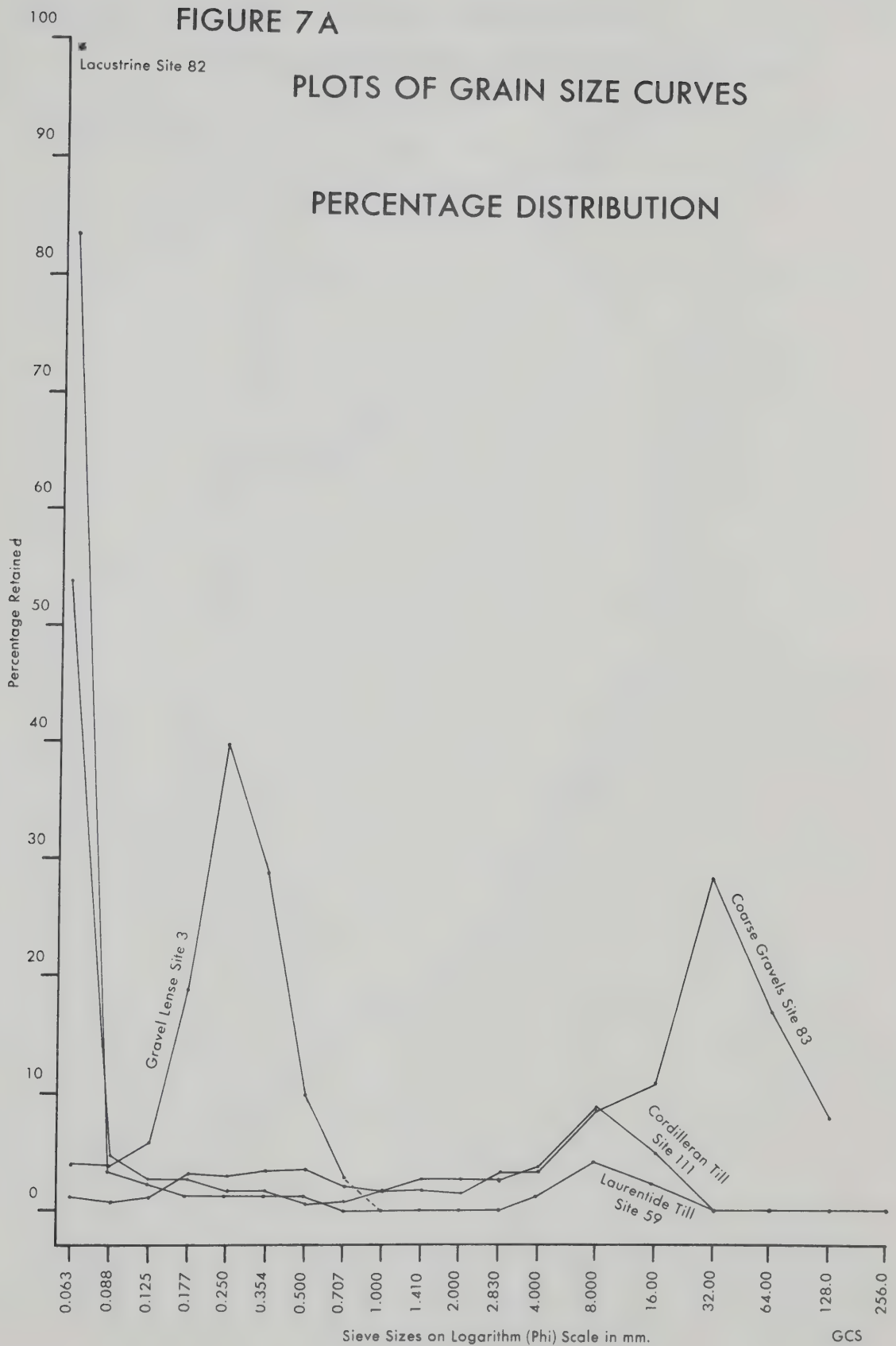


Figure 7B PLOTS OF GRAIN SIZE CURVES

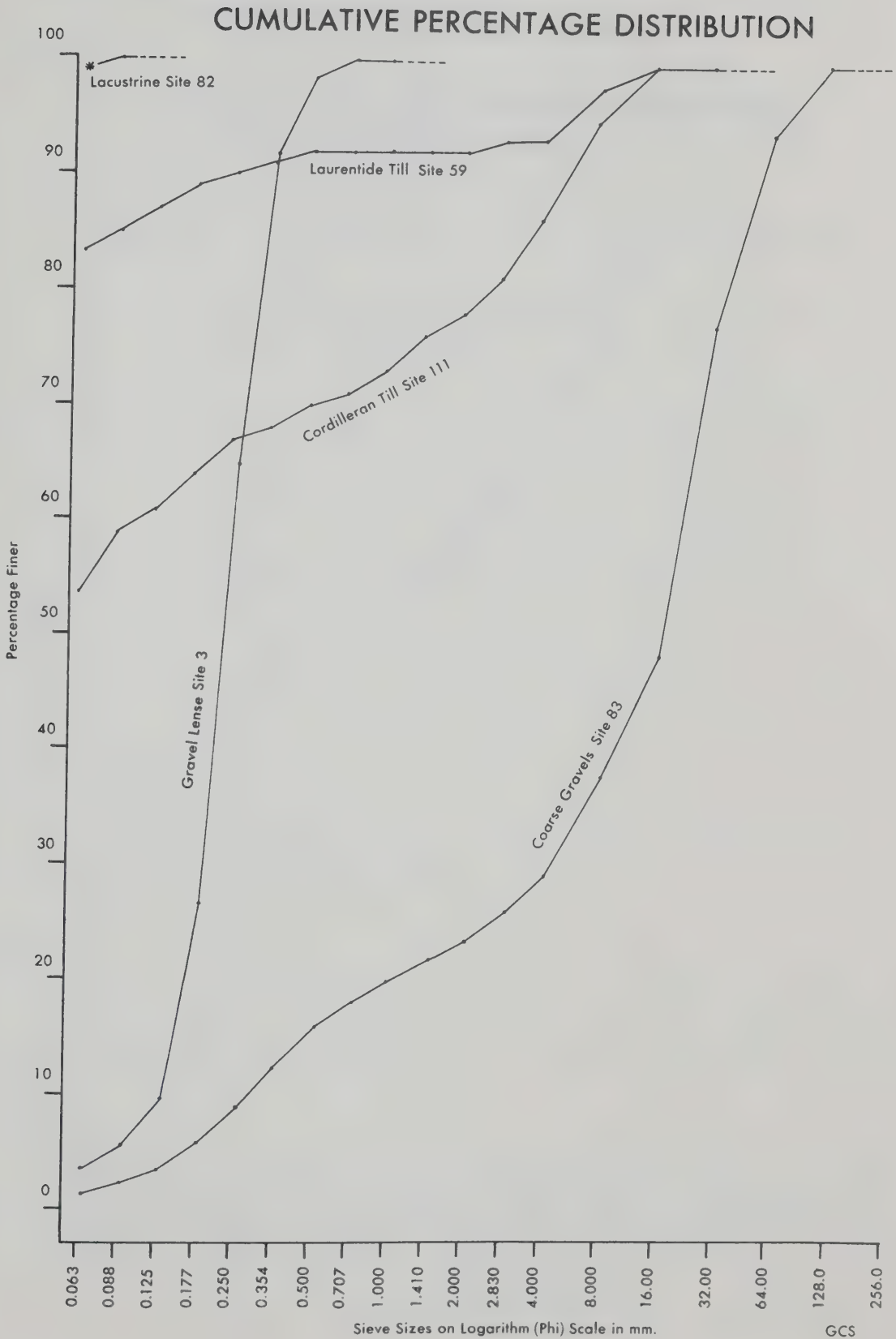
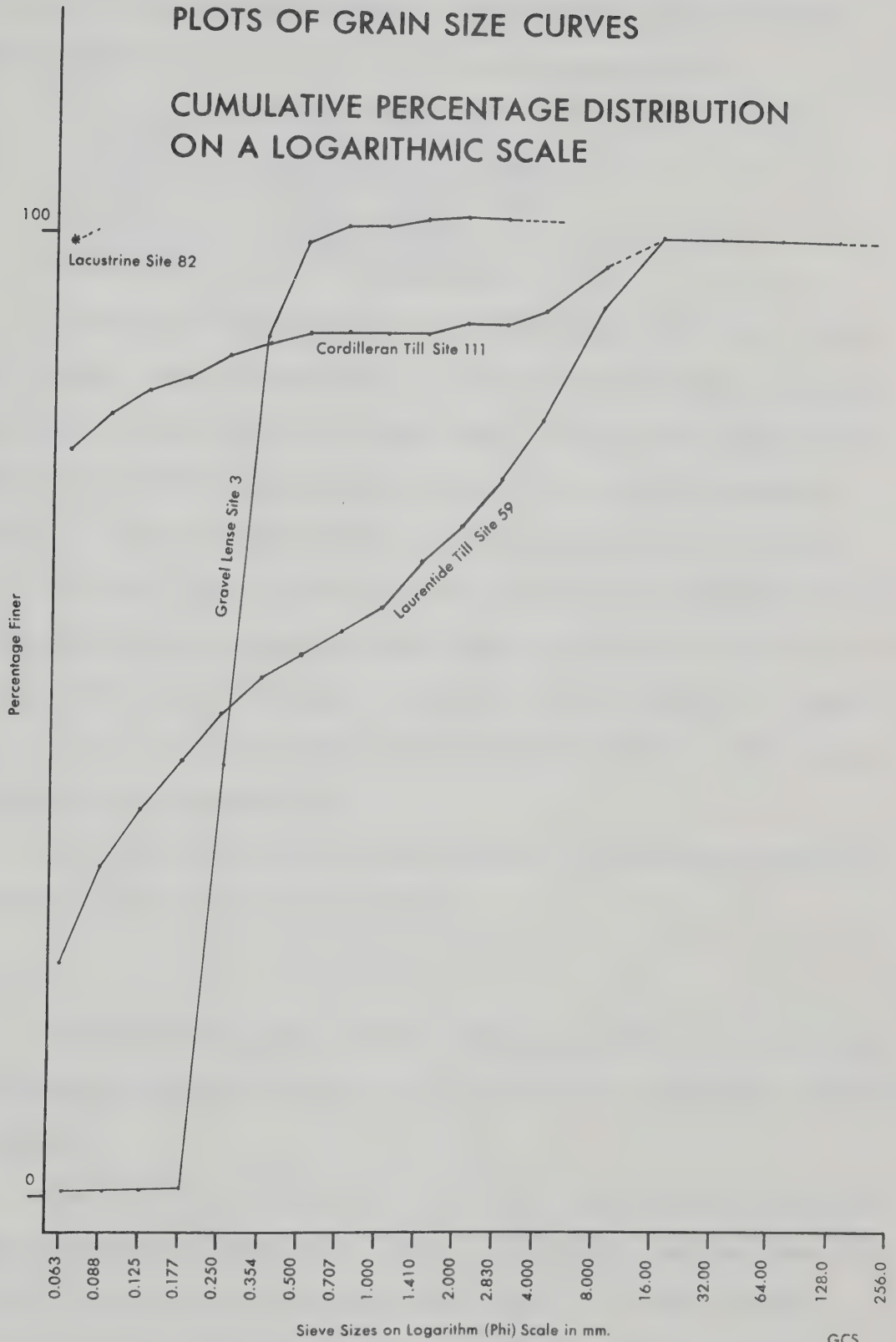


Figure 7 C



achieved by reducing the original number of grain size classes (15) to seven new classes which approximate the Wentworth (1922) scale. The following are the classes used.

< 0.063mm	Clay-silt
0.063mm to 0.125mm	Fine sand
0.125mm to 0.354mm	Medium sand
0.354mm to 1.000mm	Coarse sand
1.000mm to 2.830mm	Gravel
2.830mm to 4.000mm	Gravel and Granules
>4.000mm	Granules

Before investigating the new matrix (MO-2) of grain size classes and observations, this matrix is 'rank ordered' according to the clay-silt fraction. A computer program was prepared for this purpose (see appendix 2 for the program listing). The results of the rank ordering of the matrix (MO-2) are such that each of the original rows of observations in the matrix is arranged in an order so that the first column (of clay-silt percentages) is ranked from highest to lowest value in the resultant rank order matrix (MO-3). This matrix is presented in appendix 3.

At this point the matrix (MO-3) is studied, and the contents of the matrix described.

Step 2

The original data matrix (MO-1) is used in this step and the multivariate statistics of principal component analysis is applied.

According to Anderson (1958) the eigenvalues and the components may be generated from a covariance matrix when the original data are in a standardized form. In this study, because the data matrix (MO-1) consists of ratio numbers

(percentages) obtained from the same dimensional units, this matrix may be considered standardized. This procedure is useful since a convenient test of significance of the results is available in this case. However, for convenience, a package computer program was used (Dixon, 1968). As in most cases, programs which are prepared for this analysis automatically centre and normalize the original data, and the results are then generated from the correlation matrix. This is a more efficient computational procedure, but has the disadvantage that significance testing of the results is much less reliable and far more complicated than for the procedure using the covariance matrix.

The computer program (Dixon, 1968) is based on the generalised equation,

$$(C - \lambda I)b = 0$$

where b is the matrix whose columns are the corresponding eigenvectors to the scalar or eigenvalue λ . I is the identity matrix. Subsequently the program generates $[Z]$ the vector of standardized components of the model,

$$[Z] = [W] \cdot [y']$$

where

$[W]$ is the orthogonal matrix of coefficients and $[y']$ is the vector of standardized components given by

$$[y'] = [y]^{-\frac{1}{2}}$$

where $[y]$ is given

by the solution of,

$$[y] = [U]^t \cdot [x]$$

where $[U]^t$ is the matrix of covariance

terms (King L.J., 1969). Finally, the program rank ordered the column vectors [Z]. Appendix 4 provides a more detailed explanation of principal component analysis.

The results generated by the principal component analysis are investigated in the following manner.

The correlation matrix is checked for groups of variables and the degree of interaction of each variable one to another.

The eigenvalues and percentage of total variance explained by each component are checked in order to determine which components are most likely to produce meaningful and interpretative results. The arbitrary criteria for this step are that the eigenvalues be greater than 1.0 (King, 1969), and the level of explained variance contributed by each component be greater than or equal to 10 percent. A component satisfying these conditions is considered acceptable for interpretative purposes.

The third step involves looking for groups and combinations (clusters) of samples within the component lists which are acceptable for interpretative purposes in the previous step. The method of checking the component lists involved the following procedure.

The columns of factor loadings in each component were arranged parallel to each other, as shown in appendix 5. Since each factor score in each component was associated with a particular sediment sample, the location of each sample on each component was found. Each component was then divided

into positive and negative portions according to the values of the factor loadings in each list. Subsequently, the samples located in the positive portion of the 2nd to nth component lists (where n is the number of components accepted), were traced over the whole range of the first component. This was done on the assumption that the first component, which has the greatest explained variance and the highest eigenvalue, will produce the most interpretative results for its whole range of factor loadings. In the remaining components, the positive range of the factor loadings was used more as a means of adding information to that found in the first component. Hence, to provide a more reliable range of factor scores in the 2nd to nth components, only the positive values were considered. This first phase of locating samples on the component lists will give an indication of the behaviour of the components in terms of the varying magnitude of the factor loading attributed to each sample in each component.

The second phase of checking involved identifying every sample in the first component in terms of the original diagnosis of sediment type, made in the field for each sample. Those samples in the first component which were found in the positive portion of the 2nd to nth component, were also identified in these other components, and in the same way. In the course of locating and marking each sample, any distinctive groups or combinations of samples found within each component, and any groups or combinations identifiable in more than one component, were noted. The final grouping

of samples is then plotted in columns, component by component not by marking individual samples but in a simplified form where groups of samples of the same sediment type are shown as one unit in the column representing the component in which they were found (as shown in figures 10, 11 and 12). The clarity of the groups will give an indication of the degree of separation achieved by this form of analysis.

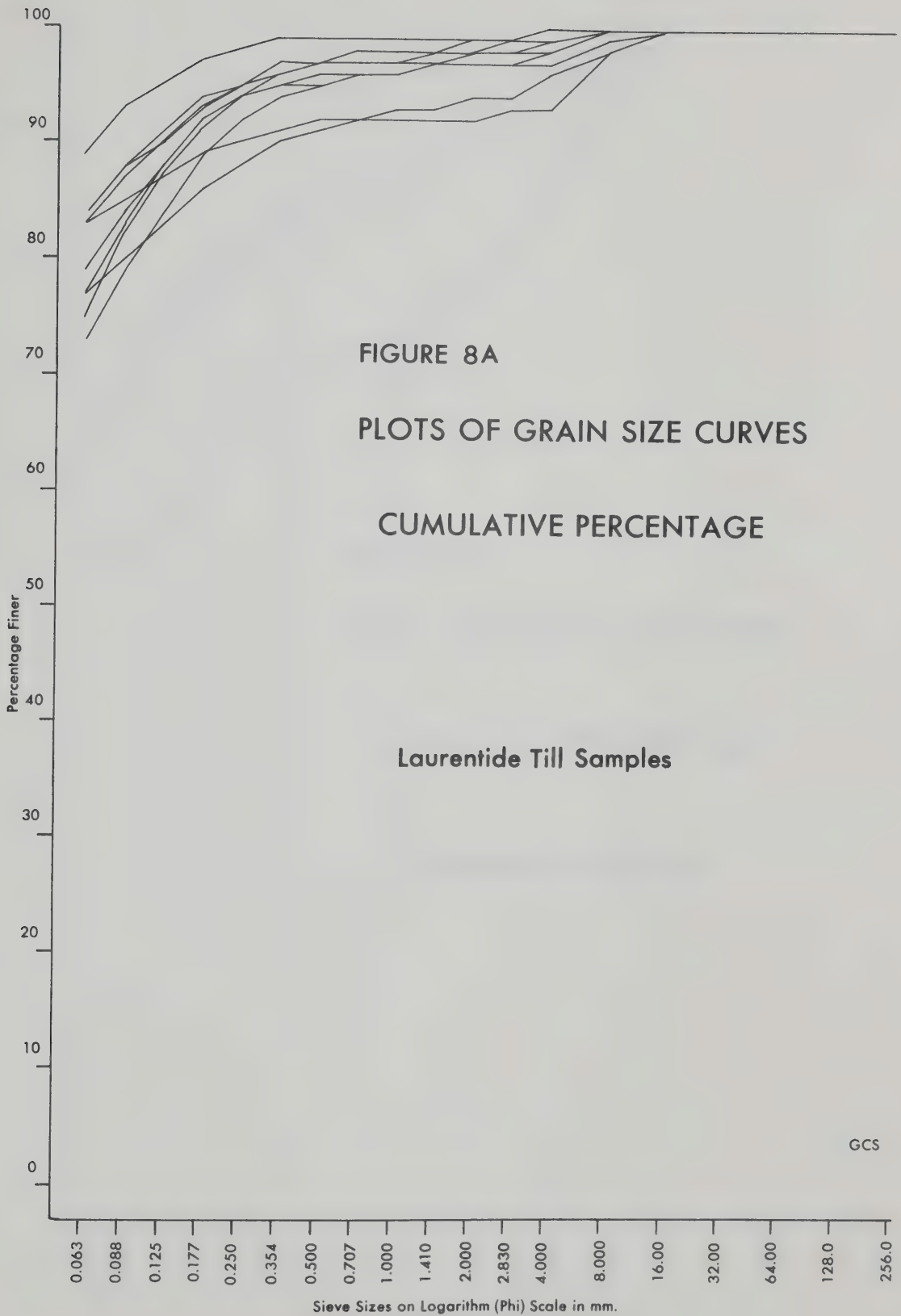
The final step is to isolate those samples which do not appear to fall into the same pattern as others with the same original sediment type diagnosis. In these cases field notes, and the original grain size data are referred to in order to identify a reason for the apparent anomalous behaviour.

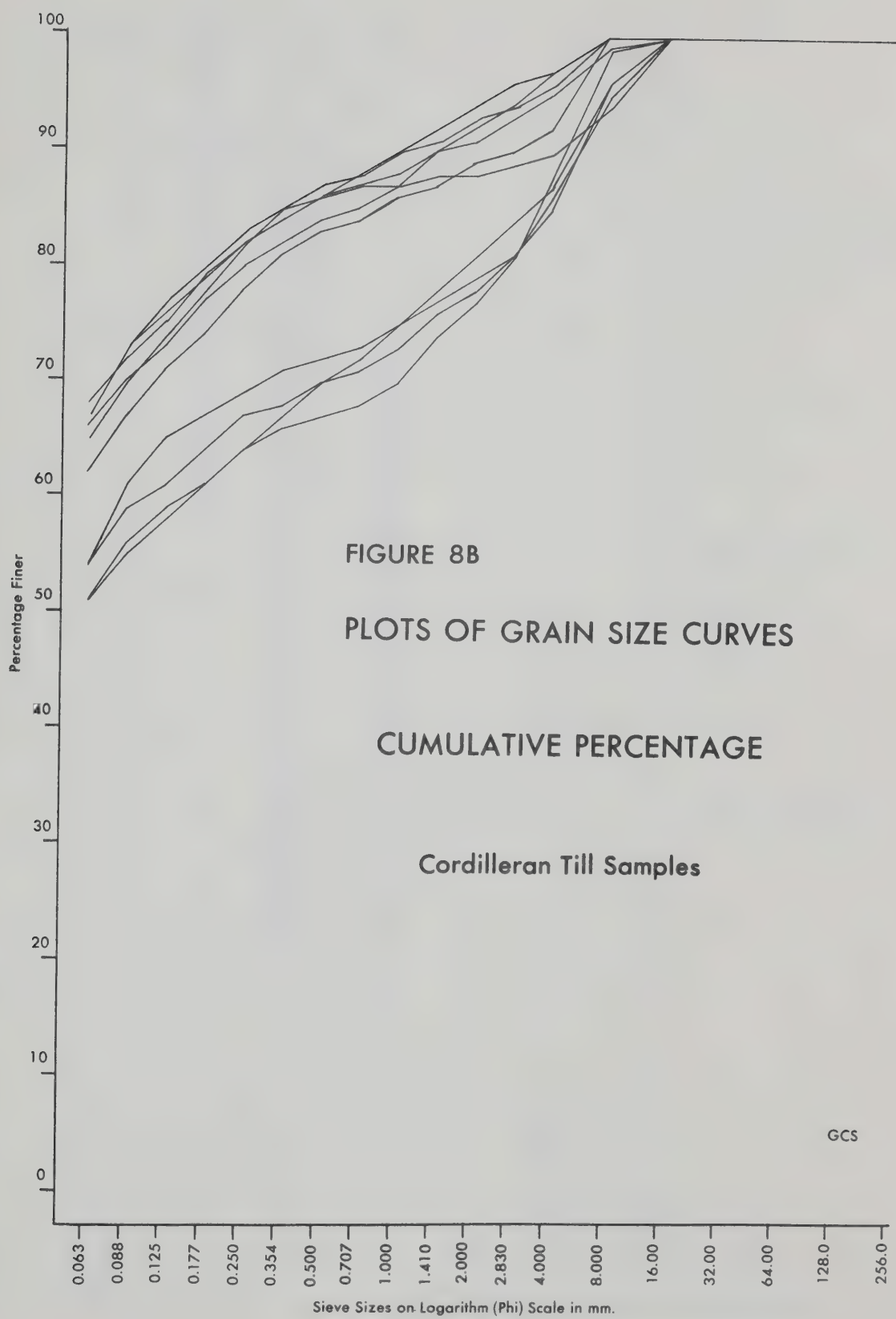
Results

The initial inspection of the plots of the percentage, cumulative percentage, and logarithmic cumulative percentage grain size data, supported an earlier assumption that the grain size curves would be too open-ended to permit use of Folk and Ward graphic statistics or moment measures. (See figure 8 for example). Therefore, the results of the analysis outlined in the previous section (under the heading of method) are presented.

Rank Order Listing

The positions of the five sediment types, marked by individual sample cases on the rank order list, are shown by sediment groups in figure 9. The length of the columns in figure 9 is proportional to the total number of samples





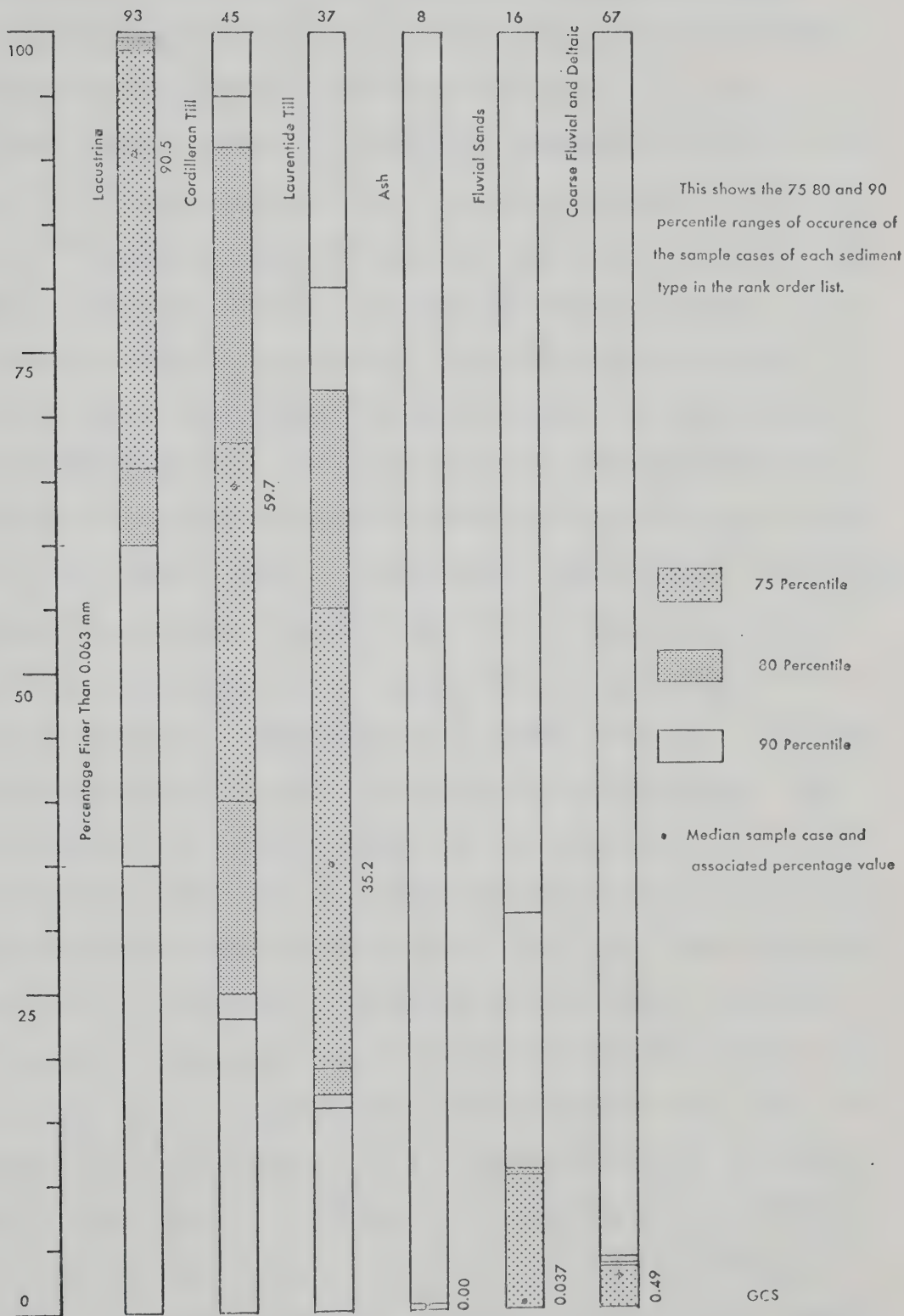


Figure 9

RESULTS OF RANK ORDER OF CLAY-SILT FRACTION

analysed. Each sediment type has been isolated from the complete rank order list so that the range of percentages over which each type is spread can be more easily seen. In all cases there is bias of the median towards one end of the scale. The median of each type characteristically falls outside the 75 percent range of each of the other sediment types, except in the case of the fluvially derived sediments. The stability of these distributions is considered not good, especially where the number of observations is below forty. Interpretation of this grouping requires the generation of new groups. The new groups are based on suppositions derived in the field, which have hitherto been unmentioned. The first postulate concerns the overlap (b) of the Laurentide till (Fig. 9) with the lacustrine types, and the overlap (a) of the lacustrine with the Laurentide till types (Fig. 9). The supposition employed, is that mixing of the two sediment types has occurred. The samples found in the overlap in each of these sediment types are all from the same area of the basin, on the southwest flank of Tower Hill (Fig. 2), where possible mudflow conditions were identified in the field. At this point these two sediment types are in contact at the foot of a long steep slope. Furthermore, these samples are from two localities above and below the presumed contact of the lake sediments with the till. Hence, the overlap (b) of figure 9 may be from the derivation zone of the mudflow on the hill slope above the lake sediments, whilst the lacustrine overlap (a) may represent the toe of the mudflow. The second

supposition is that the samples from the Laurentide till overlap (c) with Cordilleran till samples which are together spatially, may in fact be Cordilleran till.

In order to examine this new set of groups the Wentworth (1922) grain size classes of each sample were investigated (in matrix MO-2). Observation showed that the medium to coarse sand and gravel classes were useful indicators of the distinctiveness of each sediment type in the overlapping regions of the rank order listing. The lacustrine sediment samples in overlap (a) (Fig. 9) had a secondary low peaking in the medium to coarse sand and gravel classes with a magnitude of 1.5 to 4 percent. This is similar to the Laurentide till samples, except that the peaking was much lower for the samples in overlap (b) of this sediment. The Cordilleran tills show irregular peaking of the medium sands to gravels and granules classes. The magnitude of percentages in the range medium sand to gravel classes of the Cordilleran tills is slightly higher than in the same classes in most of the Laurentide tills; except those samples in overlap (c) of the latter sediment type. It is therefore believed probable that the two suppositions referred to above are valid.

Principle Component Analysis

The correlation coefficient matrix (Table 2) reflects the basic nature of the percentage values of the grain size data (matrix MO-1). As the percentage contribution of one grain size class tends toward 100 percent, so the other percentages in the vector of observations will show a greater

TABLE 2

CORRELATION MATRIX GENERATED FROM THE FIRST PHASE PRINCIPLE
COMPONENT ANALYSIS OF 15 CLASS VARIABLES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1														
2	-.5	1													
3	-.6	.9	1												
4	-.7	.5	.7	1											
5	-.8	.1	.4	.8	1										
6	-.7	-.0	.2	.5	.8	1									
7	-.7	-.1	.1	.2	.5	.8	1								
8	-.5	-.1	-.0	.0	.2	.5	.9	1							
9	-.5	-.1	-.0	-.0	.1	.3	.8	.9	1						
10	-.5	-.1	-.0	-.0	.1	.2	.6	.8	.9	1					
11	-.5	-.1	-.0	-.0	.0	.2	.5	.6	.8	.9	1				
12	-.4	-.0	-.0	-.0	.0	.1	.4	.5	.6	.8	.9	1			
13	-.4	-.0	-.0	-.1	-.0	.0	.2	.3	.5	.7	.8	.9	1		
14	-.3	-.0	-.0	-.1	-.0	.0	.2	.3	.4	.5	.6	.7	.8	1	
15	-.2	-.0	-.0	-.1	-.0	-.0	.0	.1	.1	.2	.4	.4	.5	.6	1

inverse relationship to this one class. The high percentage values of the first variable (clay-silt) indicates that the strong inverse relationships found between class one and all other classes (Table 2) are to be expected. The colinearity which may also be expected in grain size data is also evident in the correlation matrix, as adjacent values in Table 2 are mostly very similar, and the n to $n+1$ classes are all highly correlated. The exception is found in classes 2 to 5 inclusive. In this case zero values are common which suggests an independence of these classes to classes 6 to 15 inclusive. In classes 6 to 15 inclusive the original data values are small and zeros are frequent, which would explain the high n by $n+1$ correlation values of these classes once the first class has been considered.

The eigenvalues listed below (Table 3) support the acceptance of only the first four variables at the arbitrary level of 1.0 suggested by King, L. J. (1969).

In terms of a percentage contribution of each variable or component to the total variance, an arbitrary level of contribution of ten percent would reduce the acceptable number of components to three (Table 3). In fact this was the final number of components accepted. In the arguments presented previously using the rank order listing and the Wentworth groups, it was found that the third to sixth groups of this scale were used to qualify fairly obvious distinctions rather than absolutely determine them. Hence, the first and second Wentworth groups of clay-silt and fine sand respectively,

TABLE 3

EXPLAINED VARIANCE AND EIGENVALUES

FOR THE ANALYSIS OF ALL CASES

Component	Eigenvalue	Percentage Variance Explained
1	6.327	42
2	3.716	25
3	2.181	14
4	1.233	9
5	0.644	4
6	0.360	2
7	0.270	2
8	0.130	1
9	0.053	1
10	0.046	0
11	0.018	0
12	0.013	0
13	0.009	0
14	0.002	0
15	0.000	0

will reflect the behaviour of all groups. These two groups, comprised of the first four grain size classes, or variables, are accounted for in the first three components of the principal component factor listings.

The factor loadings were arrayed in rank order with each component listing adjacent one to another (Fig. 10). When the first three components had been accepted, an arbitrary datum or level of significance was established, using only values greater than unity. The first step of the interpretation involved checking the positive values of component one with those of components two, three and four. Component four was included to ensure that the major clusters were all accounted for. Those cases with positive values in all three components were found to have low percentages of clay-silt. In components two and three, all the fluvial samples had factor loadings greater than 1.5. This meant that other sediment types could not form distinct groups in the greater than 1.0 range of the factor loadings. Thus, this first step was repeated for the whole range of component one, against the positive ranges of components two and three. The designated sediment type for each sample was also listed against the respective factor loadings in each component. The reason for this repetition is based on the tendency for the development of inverse relationships between class one (clay-silt) and all others (see Table 2). In addition, the groupings of higher values in variable one will tend to produce lower ranges of factor loadings, an observation made by Gould (1967).

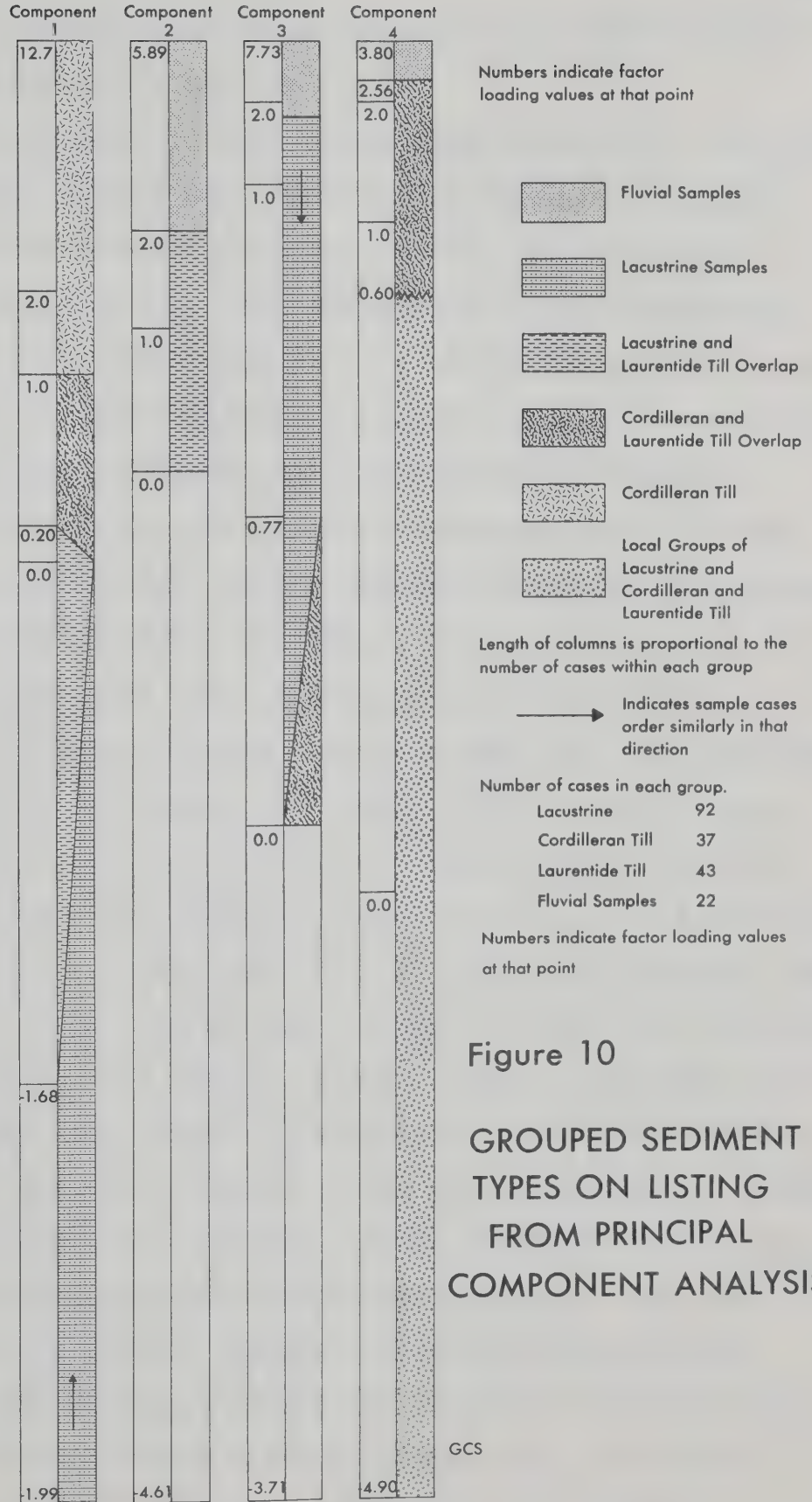


Figure 10

GROUPED SEDIMENT
TYPES ON LISTING
FROM PRINCIPAL
COMPONENT ANALYSIS

Therefore, investigation of groupings in the lower range of component one may be justified.

The results of this second phase of checking are now summarized cf figure 10. There are two dominant clusters. The first cluster is that of the fluvial, and ice wedge samples, in the greater than unity range for all components. The second cluster includes all the lake samples in the range less than zero of component one, and the range 1.1 to zero of component three. In component two only those lacustrine samples with values -1.6 to zero in component one are found. This would include less than 25 percent of all the lacustrine samples and specifically includes those from the overlap (a) (Fig. 9) in the rank order listing with Laurentide till samples (from sites located in Area B, Fig. 2). In component one these same Laurentide till samples (from Area B, Fig. 2) range from -1.2 to +1.0, whilst in component two these till samples overlap with lacustrine samples again. The Cordilleran tills are found in the range +0.35 to +12.73 of component one, except five which overlap with Laurentide samples in the range +0.35 to +1.0. This overlap is also found in component three involving the same samples in each case. No Cordilleran till samples are positively ranked in the second component. Hence, these overlapping till samples (in the component lists) lend support to the second supposition made earlier - that the Laurentide till of this overlap, which includes the same samples in the overlaps (c) and (d) of the two tills in the rank order listing (from sites in Area A, Fig. 2), may in fact be Cordilleran in type. Similarly, the overlap of

lake sediments from components one and two supports the first supposition of mudflow action between Laurentide till and lake sediments in the vicinity of Area B (Fig. 2).

The above procedure, involving principal component analysis, was repeated for the two major overlapping groups. The first overlap is between the two till types and the second is between lacustrine and Laurentide till.

The result of testing the Cordilleran and Laurentide tills together yielded very distinct cluster centered on the zero value of the factor loadings of component one (Fig. 11). The Cordilleran tills have a characteristic positive loading. All the Laurentide tills have negative values in the factor loadings except for those taken from sites in Area A (Fig. 2) near Hoodoo Ridge and Tower Ridge. Those Cordilleran till samples with negative values were collected from north of Bragg Creek. Since these two localities have no samples taken between them there is doubt concerning the correct identity of the till samples from these two areas. These results are based solely on component one, which has a 59 percent explained total variance. Despite the fact that components two and three should be considered on the basis of the explained variance and associated eigenvalues, interpretation of each of these components reflected increased mixing of types within the factor loading lists. Since component one had a high explained variance and eigenvalue, (Table 4) interpretation was based on this alone. The



Figure 11

GROUPED TILL SEDIMENTS ON LISTING FROM PRINCIPAL COMPONENT ANALYSIS

Numbers indicate factor loading values at that point

-  Cordilleran Till
-  Laurentide Till
-  Negative values

Number of cases in each group.

Cordilleran Till	37
Laurentide Till	43

Length of column is proportional to
number of cases in each group.

TABLE 4

EXPLAINED VARIANCE AND EIGENVALUES

FOR THE TWO TILLS ANALYSIS

Component	Eigenvalues	Percentage Variance Explained
1	8.90	59
2	3.43	23
3	1.13	8
4	0.69	4
5	0.38	3
6	0.20	1

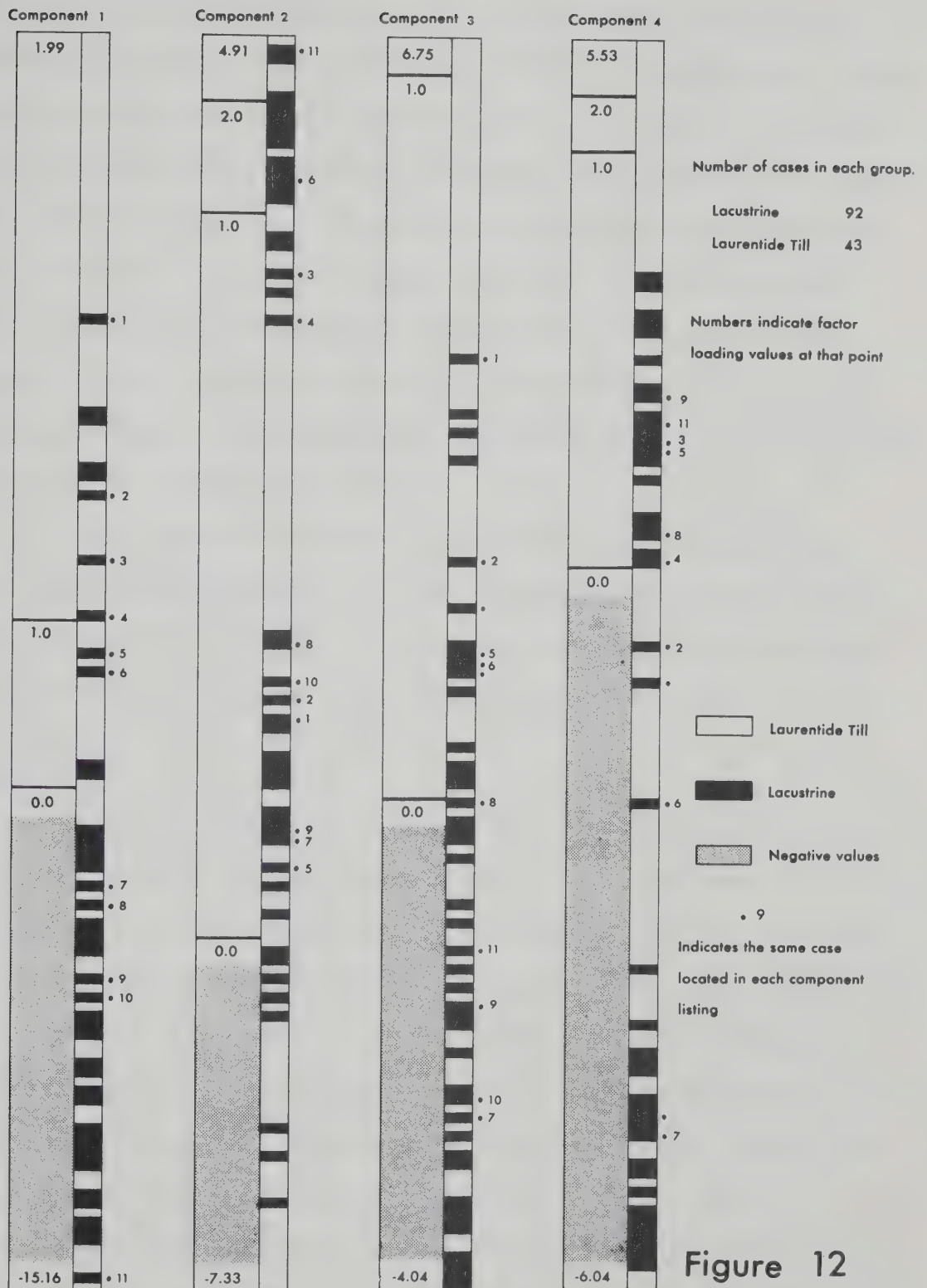
correlation matrix for this phase of the analysis showed that the first variable (the clay-silt fraction), was highly inversely related to all other variables with values greater than 0.5. All other variables were related directly with the n to $n+1$ and $n+2$ cases, all of which had coefficients greater than 0.5.

The results for the lacustrine and Laurentide till samples together (Table 5) yielded no such clear clusters. However, the results did produce certain useful characteristics. The associated correlation matrix had lower values than above. The relationships were similar overall, with locally high correlations in the low percentage variables. The eigenvalues and explained variances in each variable showed that the first four variables could be considered arbitrarily to be significant. The explained variances are very similar to those of the original analysis using principal components (Table 3). This would suggest that these two sediment types when combined, generated most of the variance of the whole range of sediments used originally. These two sediment types, which account for 70 percent of all the cases analysed, seem to create a bias in the variances generated for each component. This bias is emphasized by the previous analysis, where when the number of cases of each sediment type was similar, the ranges of values of the first component were different (Figs. 11 and 12), and distinct clusters were generated. In the present case the first and third components show similar and reasonably strong grouping (Fig. 12). The

TABLE 5

EXPLAINED VARIANCE AND EIGENVALUES FOR THE
LACUSTRINE-LAURENTIDE TILL ANALYSIS

Component	Eigenvalue	Percentage Variance Explained
1	6.45	43
2	3.45	23
3	1.88	13
4	1.31	8
5	0.71	5
6	0.50	3
7	0.35	3
8	0.20	1



GROUPED LACUSTRINE AND LAURENTIDE TILL ON LISTING FROM PRINCIPAL COMPONENT ANALYSIS

second and fourth components show similar but mixed groups. In both cases the interpretation of the first principal component analysis were not improved upon. In general therefore, this group probably reflects the bias produced by the number of cases. In addition, within group variances are important, but not great enough to produce distinct clusters within a high initial total variance. Hence, the high percentage values of the first variable (the clay-silt fraction) of the original data is insufficient to produce good differentiation of these two sediment types.

The final allocation of sediment type was made by continued investigation of the overlapping cases; and field notes and grain size data were also used. The final results were plotted on the surficial geology map (Fig. 21).

Conclusions

This experiment has shown that the behaviour of the three components is as follows. The first component tends to produce a range of factor loadings whose values are inverse to the class one grain size percentages. Only percentages of the clay-silt class less than 40 percent produced positive factor loadings. The second component is more sensitive to larger variances in the second and possibly third classes of grain sizes. This continues to produce inverse factor loadings but emphasizes stronger variance in class two with respect to class one, and thereby eliminates Cordilleran tills and most lake sediments. The third component, which brings fluvial and lacustrine samples into juxtaposition, appears to

group those cases which have extreme values in the clay-silt percentage, thereby emphasizing the maximum variance of variable one. The fourth component is far more varied in behaviour and is far less easy to interpret. This component has put all the tills and lake samples into small clusters with no sorting between types. Hence, the analysis was discontinued in the fourth component.

The analysis, which was used primarily for interpretative purposes, has shown that discrimination based on principal component analysis between a number of sediment types is possible. In addition, it indicates those cases where there is doubt as to the correct sediment type allocation and provides sufficient information for the reasons causing this doubt to be identified. In this study the analysis indicated that eleven samples had been wrongly identified, and that 23 others required additional information before definite identification could be made.

Summary

A model for the testing of hypotheses relating to the determination of sediment type and the spatial significance and pattern of the sediments could be built upon the approach used in this study. Many workers have used factor loadings as data for the statistical mapping of phenomena. A similar approach was used by Kendall (1939) for crop productivity in England. In this application it is felt that the shape of the area studied and the density and distribution of points, do not provide sufficient grounds for applying techniques of

spatial analysis such as canonical trend surface analysis (Lee, 1969) to the data obtained. Sampling methods which would however, permit such research are as follows:

1. A regular or more even distribution of sample points for any given scale. The juxtaposed nature of contrasting sediments encountered in this study suggest that a small area be used initially, so that mapping criteria (e.g., for isoline) may be evaluated. (Ogawara and Yamazaki, 1952).
2. More complete granulometric data will give an improved grouping of factor loadings within components and allow the mapping of component by component.
3. The inclusion of additional variables.
4. Finally, the researcher must develop criteria by which the delimitation of areas may be achieved according to basic geomorphological considerations.

A possible avenue for future research could involve two or three new variables. The object would be to identify spatial patterns similar to those found by conventional methods.

In conclusion therefore, the finding is that principal component analysis can be used to discriminate between known sediment types. It may also be used to identify sediment groups not easily distinguishable. The usefulness of principal component analysis lies in its flexibility in terms of identifying factor loadings for every sample. The differences in grouping within each component are the expression of within group variances and hence this technique conveniently expresses

the limitations of the original data. The major disadvantages of principal component analysis seem to be the difficulty of applying significance tests, and the more fundamental fact that principal component analysis does not give any idea of error variance except by interpretation.

CHAPTER III

RECENT GEOLOGICAL HISTORY OF THE ELBOW RIVER BASIN.

Several general statements have been made by Beach (1943) concerning the study area, and the author concurs with these. The first emphasises structural control.

"the markedly different resistance to erosion offered by the various lithological units of the bedrock has been the controlling factor determining the nature of the topography . . . The ridges mark the outcrops of massive sandstone and conglomerate beds and the flat-bottomed valleys those of formations composed predominately of shales."

Beach also recognised a major discordant feature.

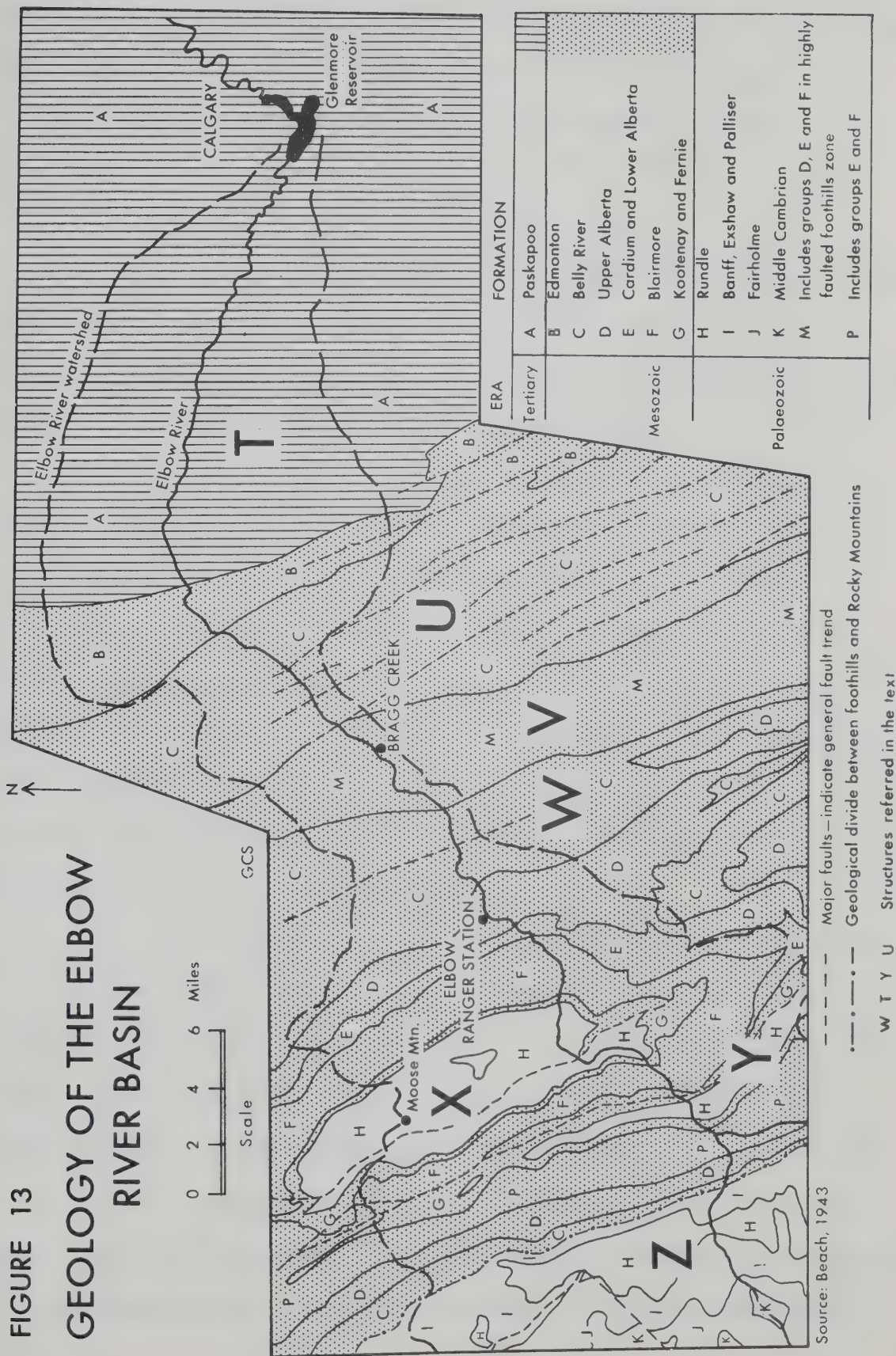
"The foothills part of the region is dominated by one major topographic feature, Moose Mountain Dome. . . . Streams have cut several deep canyons across the dome."

Except for a few Tertiary and late Cretaceous outcrops found east of Last Break Hill, these quotations summarise the major morphological units of the area. The Tertiary strata which underlie this area of lowest relief (termed Prairie in Chapter I) are soft sandstones and shales of the Edmonton, Upper Alberta, Belly River and Paskapoo formations.

Figure 13 illustrates the dominant northwest to southeast trend of the geological strata and structural geology. The highly folded and faulted foothills regions bring the Palaeozoic sandstones, dolomites, dolomitic limestones and conglomerates into juxtaposition with Mesozoic shales and sandstones of a less resistant nature. To the

FIGURE 13

GEOLOGY OF THE ELBOW RIVER BASIN



east, the late Cretaceous rocks are faulted where they overlies the eastward extending Mesozoic and Palaeozoic rocks. The Elbow River is discordant with the geological trends

The Problem

This discordance between the course of the Elbow River and the orientation of the geological structure within the foothills poses the problem of how this situation arose. The four solutions considered are outlined below.

1. The concept of river capture was considered by Sissons (1960) to be important in the evolution of drainage in southern Scotland. In the study area, river capture may be responsible for the discordance of drainage and structure. This process could facilitate diversion of flow from structurally controlled valleys into valleys which are discordant to structure. In order to test the hypothesis of river capture, alignment of present rivers and the presence of windgaps should be investigated.

2. The breaching of watersheds by glacial ice is an alternative method by which rivers may be diverted from one drainage system or channel to another. Similar features to those associated with river capture together with glacial features will identify this type of process.

3. A process frequently considered in a region in which there is a problem of discordance of river to structure, is superimposition. The application of the superimposition

concept to explain discordance is described by Wooldridge and Linton (1955). The concept implies the existence of a drainage pattern on a surface prior to the initiation of rejuvenation of the drainage system which is superimposed. This surface may be either a re-cycled peneplain or a recently emerged sea-floor. The passage of time sees the down cutting of river channels due to isostatic and/or eustatic change, such that the rivers will eventually be established in rocks of an older period than those from which it was initiated and discordant with the structure of these rocks. At this point the river is said to be superimposed. This process specifically excludes orogenic effects but admits epeirogenesis. The evidence cited for the process may include remnants of the original surface or sedimentary cover from which the drainage was developed. Without information relating to the presence of the original surface, it becomes very difficult to infer that this process has operated within a region.

4. The process of antecedence implies that a river is able to maintain its course whilst the bedrock and the ground surface over which it flows are subject to orogenic disturbances. The river is able to downcut at a rate which is greater than the rate at which structurally controlled ridges are formed. The process has been described by Sparks (1964) as ". . . the last resort of a geomorphologist seeking to explain inconsequent drainage, . . ." because it involves ". . . guesses as to the rate of uprising folds and the rate of downcutting of rivers, about neither of which is very much

known." However, if the period of formation of geologic structures can be associated with the period which post-dates the beginning of the present phase of sub-aerial denudation, then antecedence may be implied. In this situation the presence of bedrock benches along the valley sides would help to substantiate the hypothesis of antecedence.

The background of each of these four possible solutions to the discordance of rivers is geological. The decision that any one particular process is responsible for the situation will depend upon the morphological information available. The geological and morphological factors which have been found in the study area follow.

Late Mesozoic and Tertiary Geology of the Study Area and Environs

Late Cretaceous

The basal formations of the late Cretaceous geology show evidence of a marine environment. Above the basal formations are sandstones and conglomerates in which Beach (1943) found pieces of bone (at Quirk Creek, in the Elbow basin) later identified as dinosaur bones (a femur and jaw bone). The sandstones form a part of the Edmonton formation.

Tertiary

The first well established event in the Tertiary era is the depositional phase of the Paskapoo formation. According to Tozer (1956) the Paskapoo formation is of sub-aerial origin throughout in the vicinity of the Elbow River, because

the recession of the marine environment had begun in late Cretaceous times as the Wapiabi Sea became restricted to the Alberta syncline. Formation of the Paskapoo deposit continued through Paleocene times into the Eocene period. Thereafter deposition was irregular as the earth movements of the Laramide orogeny, which began in mid-Eocene times, interrupted the spatial continuity of the Paskapoo evident in Paleocene times. The Laramide orogeny continued throughout the rest of the Tertiary period.

Distribution

The map of the geology of the Elbow basin (Fig. 13) shows that the Paskapoo formation is found in the Prairie region alone. The Edmonton formation, which includes the Bearpaw equivalents, is found along the boundary zone between the foothills and the Prairies (Beach, 1943). The Belly River formation outcrops in a synclinal structure on the west side of the Edmonton formation (Fig 13). The Belly River formation is also found faulted against Palaeozoic rocks of the Rocky Mountains, along the Rocky Mountain-foothills boundary (Beach, 1943). All rocks older than the Belly River formation outcrop west of Bragg Creek.

In the mapped area of figure 13 are seven major structural units. To the west are the Palaeozoic strata of the Rocky Mountains (Z), (Fig. 13). Highly faulted and intensely folded, this area has high relief and a complex structure. To the east is an area (Y) separated from the Rocky Mountains by a major thrust, known as the Nihahi Thrust because of its

location on the eastern flanks of Nihahi Ridge. This is the area of the Forgetmenot Anticline (Fig. 13). North and east of the latter is the prominent structural and topographic form of the Moose Mountain Dome (X). Both of these anticlinal structures cause outcropping of Palaeozoic strata (Fig. 13). East of Moose Mountain Dome is a faulted syncline in late Mesozoic strata (W). This area is flanked on the eastern side by highly faulted strata of early-middle Mesozoic rocks, which form a low anticlinal structure (V). The eastern limb of the latter slopes eastward, and is covered by late Mesozoic strata which are highly faulted in area (U). The most easterly area (T) is not folded and, except for the juncture with area (U), not affected by faulting. The area (T) is formed by the Paskapoo formation.

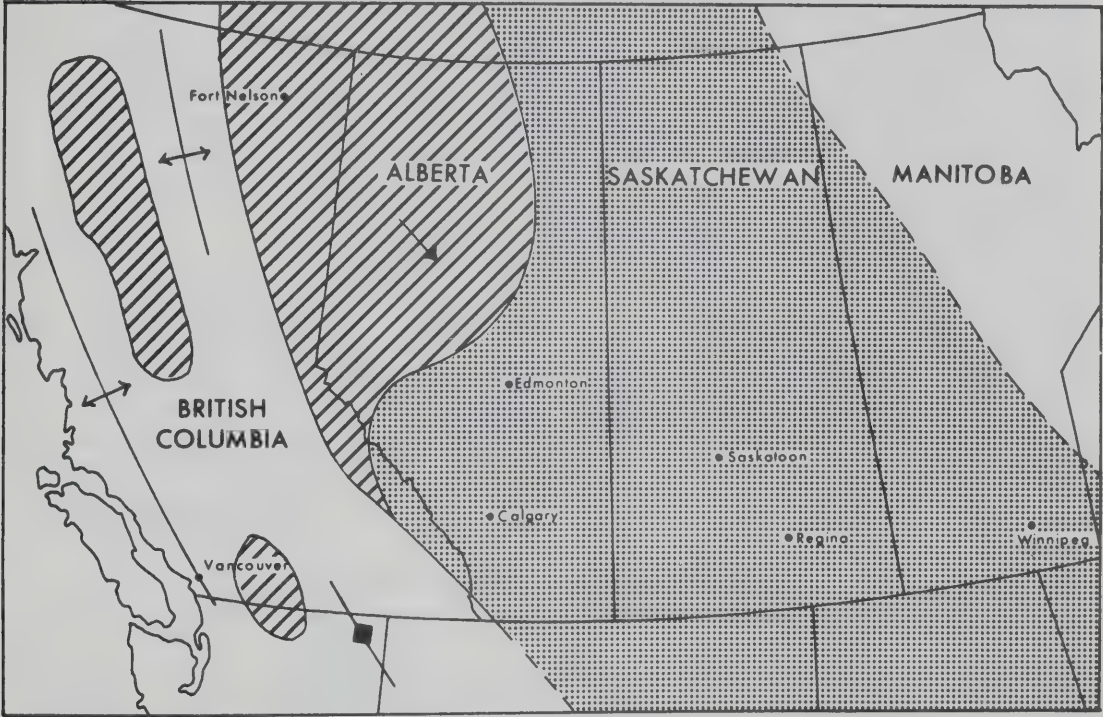
Geological History of the Environs of the Study Area

The work of McCrossan and Glaister (1964) shows that during the period in which the Belly River formation was being deposited, the area of the associated marine environment was decreasing (Fig. 14, A-F). By the end of this period, the foothills of Alberta were exposed to a sub-aerial environment, whilst the marine basin extended south from southeastern Alberta. The subsequent depositional phase associated with the Edmonton formation was marked by a western shoreline in a similar position to that of the end of the Belly River period (Fig. 14), but the marine basin now extended much further east into southern Saskatchewan and southwestern Manitoba. The western margin of this basin, which was located

UPPER CRETACEOUS PALAEOGEOGRAPHY OF WESTERN CANADA

FIGURE 14 A

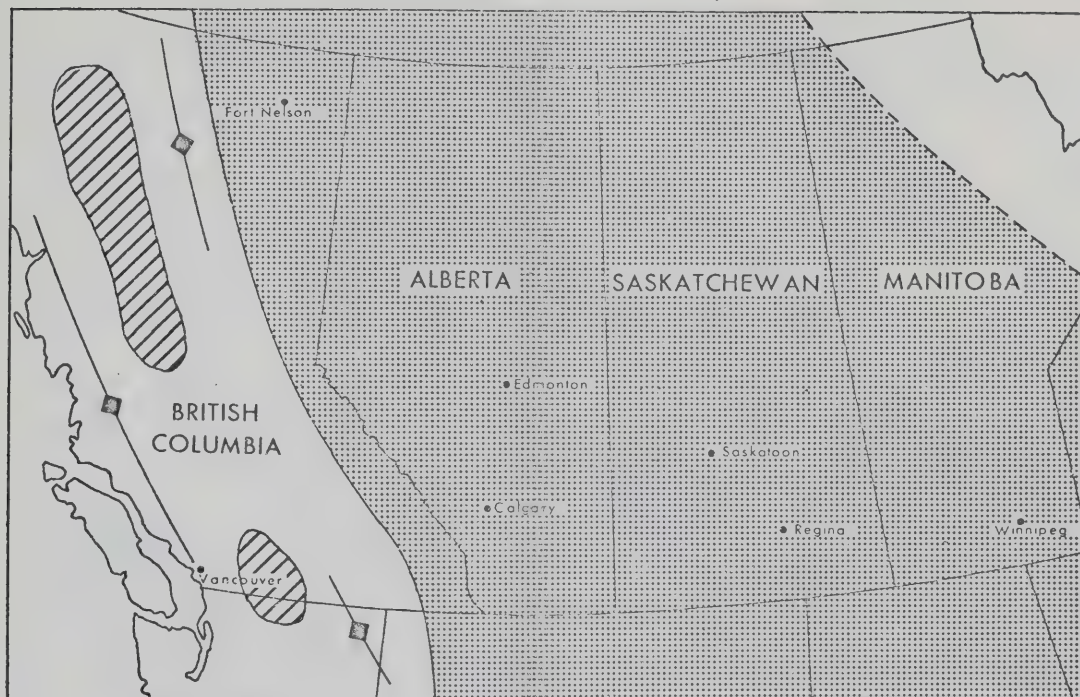
DUNVEGAN SEA (Cenomanian)



Source : McCrossan and Glaister , 1964 , p. 187 .

- ← Direction of coarse clastic supply
- ↔ Moderate to strong positive area
- ◆ Weakly positive area
- ▨ Continental deposition
- ▤ Erosion or non-deposition
- ▦ Marine deposition

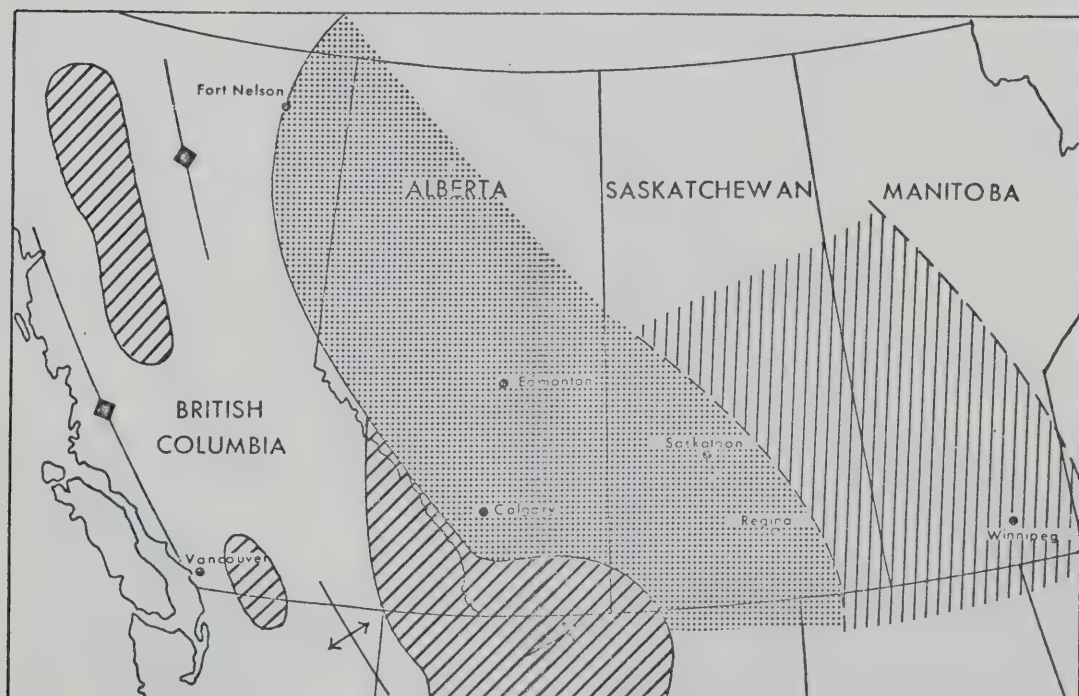
WAPIABI SEA (Santonian)



Source : McCrossan and Gloister , 1964 , p. 187 .

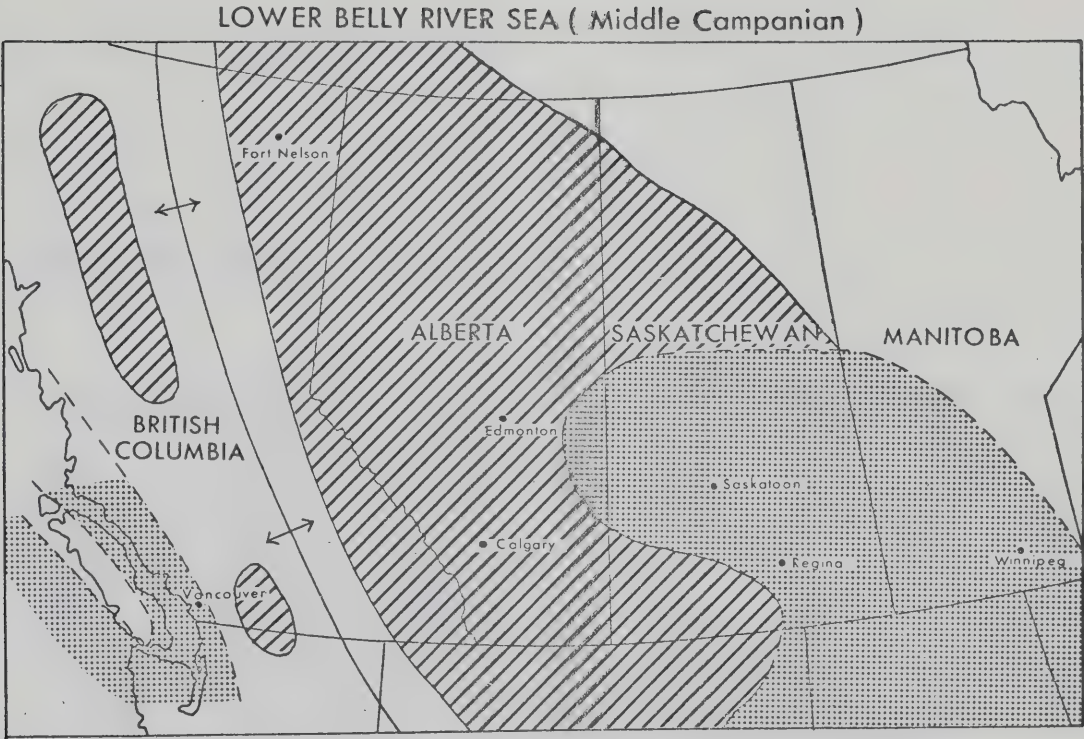
FIGURE 14C

MILK RIVER SEA (Lower Campanian)



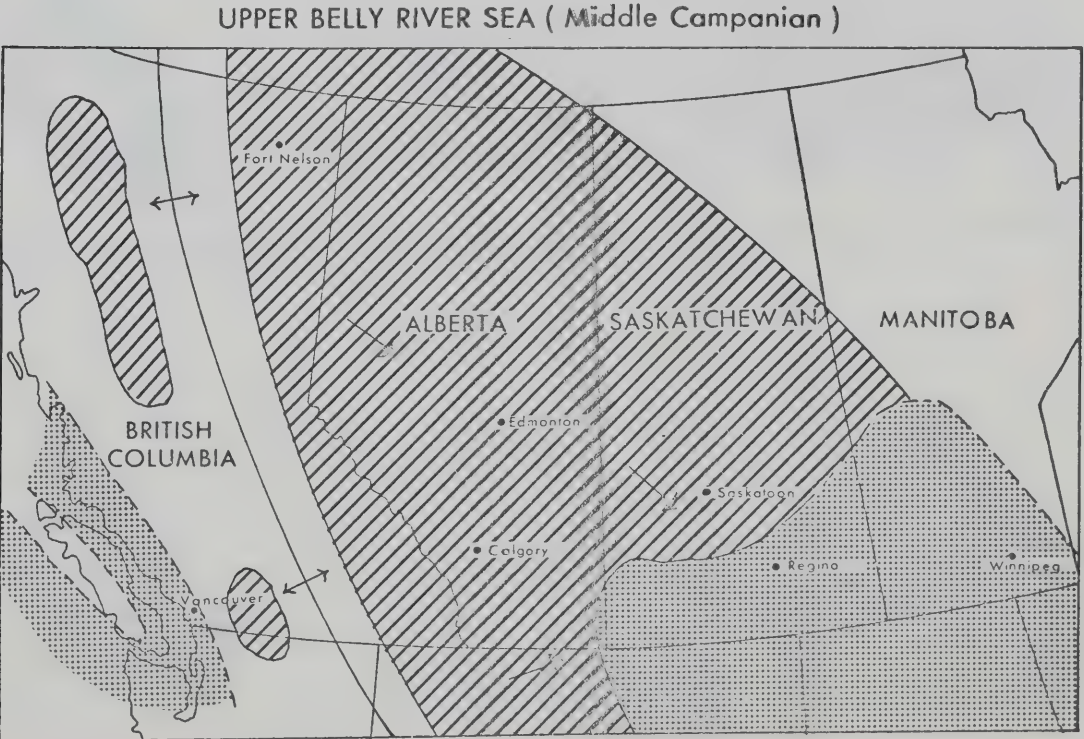
Source : McCrossan and Gloister , 1964 , p. 187 .

FIGURE 14D



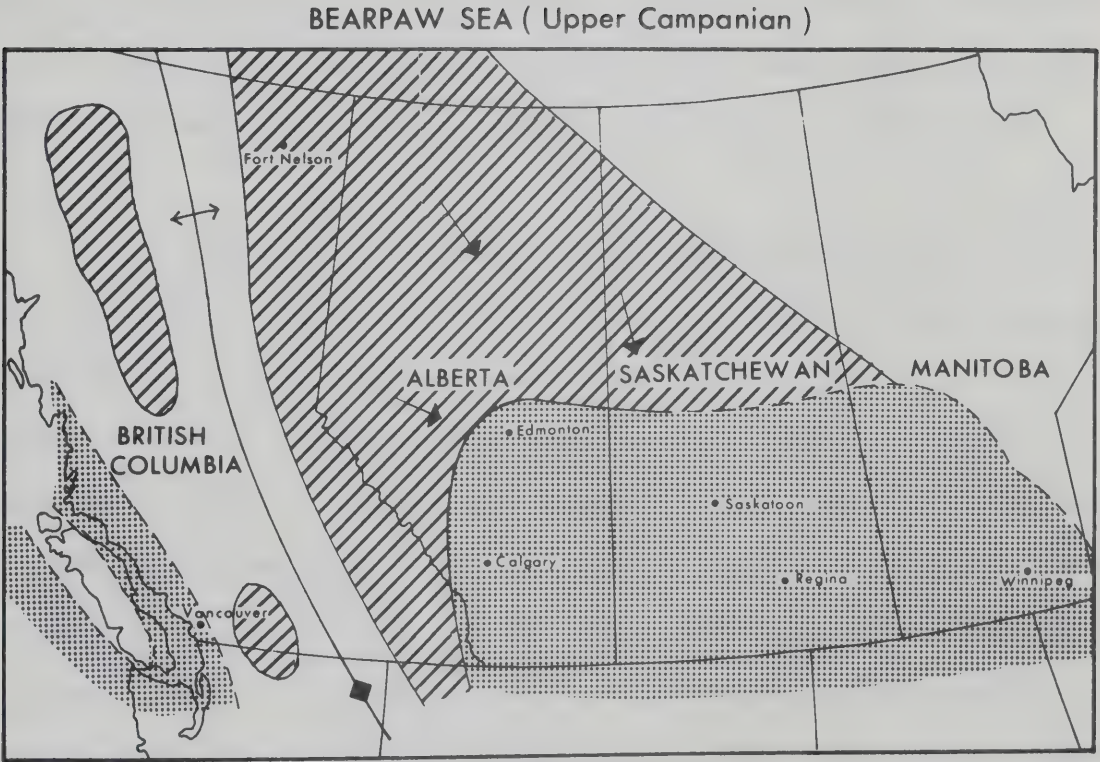
Source : McCrossan and Glaister , 1964 , p. 187 .

FIGURE 14 E



Source : McCrossan and Glaister , 1964 , p. 187 .

FIGURE 14F



Source : McCrossan and Glaister , 1964 , p. 187 .

in the study area, oscillated locally such that marine deposits are found overlayen by sandstones and conglomerates, as Beach (1943) describes in the Elbow basin. Russell (1957) suggested that the oscillations were caused by epeirogenetic adjustments of the land surface. Hence, at the end of the late Cretaceous period and the beginning of the Tertiary era uplift associated with the pre-Laramide disturbances began, and marks the extension of the sub-aerial environment already existing in eastern British Columbia and western Alberta over the larger part of southern Alberta and specifically, the whole of the study area.

The Paleocene period is suggested by Russell (1932, 1950 and 1957), Elliot (1958), and Tozer (1956) as the period of formation of the Paskapoo stratigraphic unit. The Laramide orogeny began in Eocene times and continued throughout the Oligocene period. No distinct depositional phase is associated with these two periods. Minor earth movements are thought to have occurred in Miocene and Pliocene times by McCrossan and Glaister (1964). In addition there is evidence for sub-aerial depositional phases during these two periods for several very local areas. To the west of Calgary (30 miles) are the Crawford Hills which are capped by gravels (at an elevation of 4,400 feet) as are the Hand and Wintering Hills of central Alberta. The problems associated with the interpretation of gravels found on isolated upland surfaces in Alberta have been widely discussed by Westgate (1965) and Crickmay (1965) for the Cypress Hills in southeastern Alberta.

Topography of the Study Area and Environs

The topography of the Elbow basin shows a general decline in the elevation of summit peaks from west to east (Fig. 15). There are distinct areas of homogeneous topography (Fig. 15) close to an elevation of 4500 feet, and in the eastern foothills several flat topped hills rising up to 5000 and 5500 feet were found. No bench features were found associated with the bedrock topography.

The bedrock topography and pre-glacial channels of the southern part of Alberta have been mapped by Geiger (1965), Farvolden (1963), Stalker (1961) and Carlson (1969, 1969A and 1970). None of these works have mapped a pre-glacial valley in the present Elbow basin. However, Farvolden (1963) was able to trace the pre-glacial valley of the Highwood River (in southern Alberta, 50 miles south of Bragg Creek) from the foothills onto the Prairies, although he points out that there is a break in the alignment of the preglacial valley between these two regions. In the case of the Elbow River, Farvolden traced a bedrock valley westward from a point seven miles south of Calgary up to the beginning of the foothills near Priddis, but not into the foothills. In the work of Geiger (1965), Farvolden (1963), and Stalker (1961) pre-glacial bedrock channels, other than those of the Oldman, Bow and Red Deer rivers, are not traceable into the foothills.

There is a lack of additional morphological information for the Elbow basin in the literature. In view of this, analysis of the topography was carried out in order to

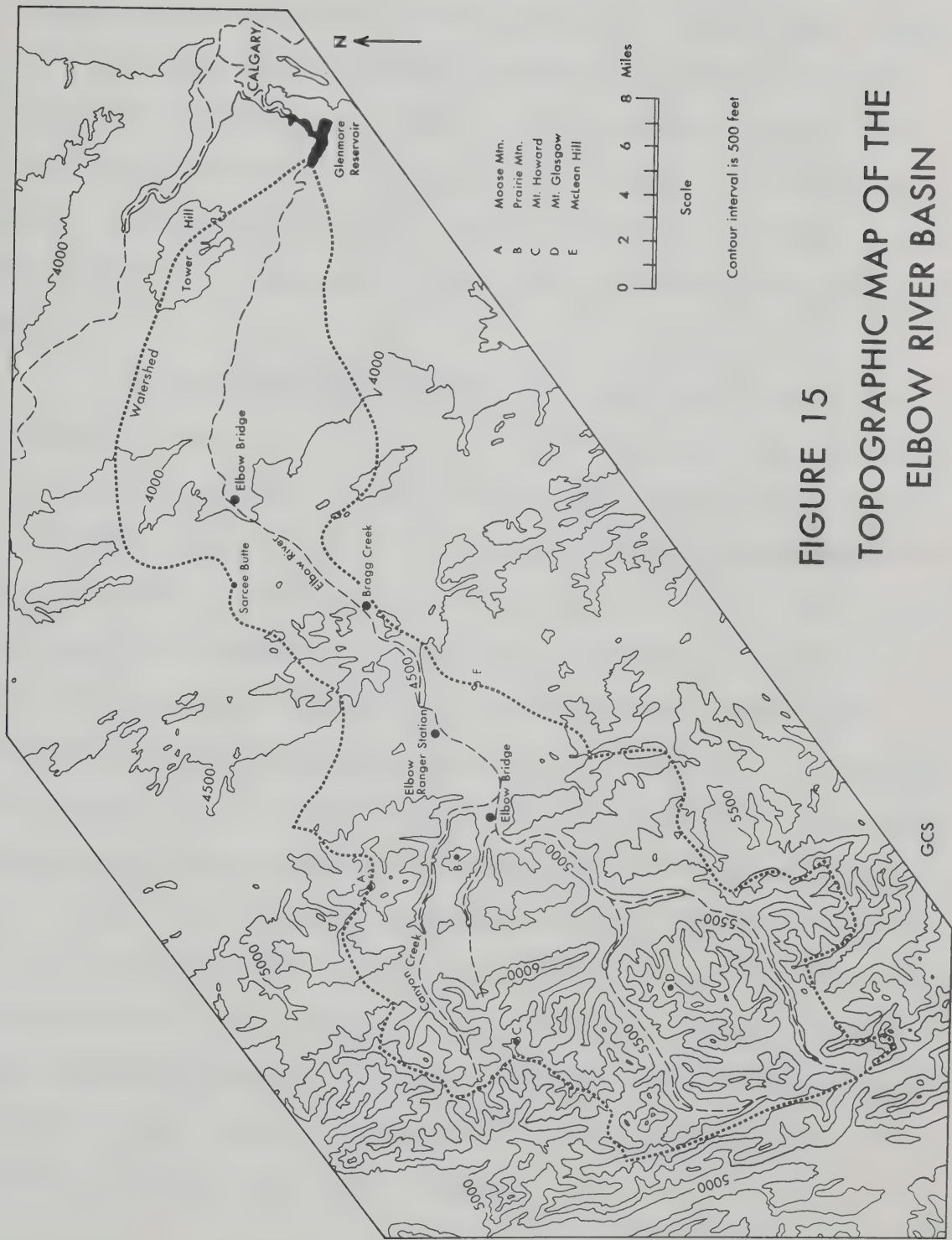


FIGURE 15
TOPOGRAPHIC MAP OF THE
ELBOW RIVER BASIN

identify morphological relationships between high and low elevations, and the major topographic units. There are several techniques which may be used for this purpose, many of which have been discussed by Pannekoek (1967). In this study two techniques are used, namely isoline mapping and trend surface analysis (King, C.A.M., 1969). The data consists of the elevations of summit peaks from the Elbow basin. The method of collection of this data is given in appendix 6, part 1.

It is generally hypothesised that summit peaks are remnants of an older surface on which drainage was initiated (an erosion surface). Based on this assumption many workers in various parts of the world have used summit peak information in order to identify an erosion surface. In this study the peaks are assumed to be useful indicators of an older phase of drainage initiation. It is considered that the distribution of summit peaks and the relationship of one peak to another will be more reliable for interpretative purposes than the specific location and elevation of a single peak.

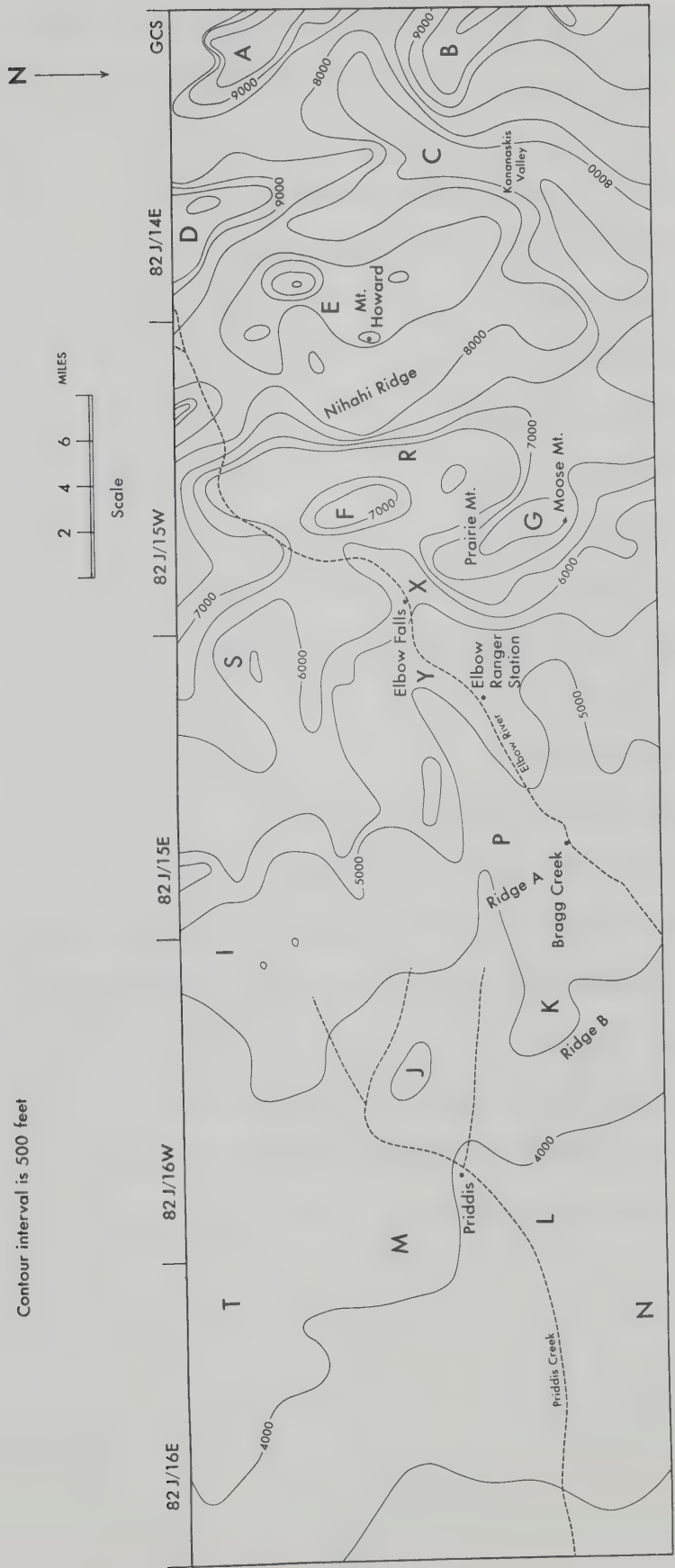
The two forms of analysis to be used both establish a form of continuity between data points. It should therefore be stated that the contour lines drawn are generalisations of an unknown morphological form, and that the interpretations based on the results are therefore made about the distributional aspect of the summit peaks.

Isoline Map of Summit Peaks

The data is plotted (as in figure 16), and a system

ISOLINE MAP OF SUMMIT PEAKS IN THE ELBOW BASIN

Figure 16



LIST OF REFERENCE POINTS FOR
FIGURES 16 and 18

A		Rocky Mountains West of Kananaskis
B		Rocky Mountains West of Kananaskis
C		Kananaskis Valley
D		Mount Glasgow
E		Mount Howard Complex
F		Rainy Creek Complex
G		Moose Mountain Dome
I		Region of Small Hills--Watershed Zone
J		Outlier of the 4500 feet "plateau"
K		Sarcee Ridge
L		Priddis Valley
M		Region of Small Hills
N		Watershed--Elbow River/Priddis Creek
P		Major Bedrock Valley of Pre-glacial Elbow River
R		Foothills--Rocky Mountains Geological Divide
S		Quirk Mountain
T		Watershed--Priddis Creek/Sheep River
X		Valley Reference Point Referred to in Text
Y		Valley Reference Point Referred to in Text

of contouring applied to generate a best fit for the data points obtained. The location of contours is made subjectively, according to the best fit generated by a given set of circumstances.

Trend Surface Analysis of Summit Peaks

An account of the statistical procedure for trend surface is given in appendix 6, part 2 (see King, C.A.M., 1967). The computations were made using a computer program prepared by O'Leary, Lippert and Spitz (1966).

The assumptions made when applying trend surface analysis to summit peaks in the Elbow basin are listed below.

(i) The summit peaks will reflect the basic spatial pattern of high and low elevations of the area, despite lowering of the points since the initial phase of incision.

(ii) Since no bedrock benches were found in the basin, the surface fitted by trend surface analysis will not reflect any one geomorphic surface (Brown, 1957), but an average "trend" surface which may be used to interpret the major valley trends. Hence, the surface derived is not the erosion surface, but an indicator of the form of the surface being considered.

(iii) The nature of the "trend" surface further emphasises that the trend is not the surface of initiation of erosion, which was conceived as a multitude of phases of development dependent on uplift and most probably reflected in benches

(iv) The asset of the trend surface is that 'noise'

(Board, 1965) or local components (Allen and Krumbein, 1962) of the topography are removed. These are presented as residuals.

(v) The residuals are assumed to reflect structures which will either indicate the main reasons underlying the discordance of the river to the geological structures, or the independence of topography from geological structure.

The reasons which necessitate the above assumptions were most clearly described by Tarrant (1970) in his criticism of the work of C.A.M. King (1969).

In 1969 King applied the technique of trend surface analysis to summit peak data for the Alston and Askrigg blocks of the Central Pennines of England. Tarrant (1970) indicated that the surface fitted by trend surface analysis does not envelope the summit peaks, as King suggested it would. Instead, the surface is fitted in the same way as a least squares regression line. The statistics of trend surface analysis require that the surface be arranged such that the magnitude of the deviations below the surface equal those occurring above the surface. The positive residuals are not identifiable as monadnocks. Therefore, the trend surface does not reflect the form of the erosion surface as C.A.M. King (1969) had implied. However, in trend surface analysis the relationship is such that more than two observations will affect the relationship of a third and locationally intermediary point. In addition, the generalising effect of trend surface analysis suggests that forms evident within the trend

of the surface are dependent upon the data and not the technique. This does not mean that details of the elevation of the trend surface specifically identify the location of the components of the erosion surface, nor does it indicate that an erosion surface existed. It does however, identify any major topographic phenomena in the area studied.

Results of Analysis of Summit Peaks

The Isoline Map

The results are shown in figure 16. The major features are indicated by letters (the names of which are indexed on the page following figure 16)

The relief shown on the isoline map (Fig. 16) increases westwards from a line north-south through Bragg Creek. To the east of this line the relief is low and reasonably smooth. This may indicate that statistically the data for peaks east of this line reflect colinearity to a greater extent than data for peaks west of the line.

The topographic forms found west of the north-south line through Bragg Creek are largely related to geological structures, for instance (Fig. 16) Moose Mountain Anticline (G), Forgetmenot Anticline (F), Nihahi Syncline (R), Mount Howard complex (Fairholme Anticline (E)), Kananaskis fault line (C), and the Barwell Syncline (S). The topography of the Rocky Mountain-foothills area would seem therefore, to be dependent upon geological structure.

The topography east of the north-south Bragg Creek

line cannot be closely related to geological structure, and may be considered to be independent of structure.

Preliminary investigation suggests that the Elbow River is closely aligned to topographic depressions, or valleys in figure 16. Further inspection shows that at only one point does the river conform with such a depression. This point is marked (X) on figure 16. Elsewhere, the river is aligned to, but not centred on the low areas proximal to its course. At point (Y), the Elbow River appears to diverge from a major valley (P) which can be traced eastwards to Priddis (Fig 16). The Elbow River flows northeast from point (Y) and cuts across the entrance to Bragg Creek valley (Q).

The rivers east of the north-south line through Bragg Creek are accordant with the valley forms mapped from the summit peaks. It is noticeable that the present Priddis Creek occupies the major valley (P), but not completely. As with other present day rivers in the eastern area, Priddis Creek headwaters are all in the same area.

The Trend Surfaces

The results of the analysis are shown in figures 17 and 18, where only the sixth order surface and associated residuals have been mapped. Inspection of the first through sixth order surfaces showed that the sixth order surface was the most useful for the reasons given below.

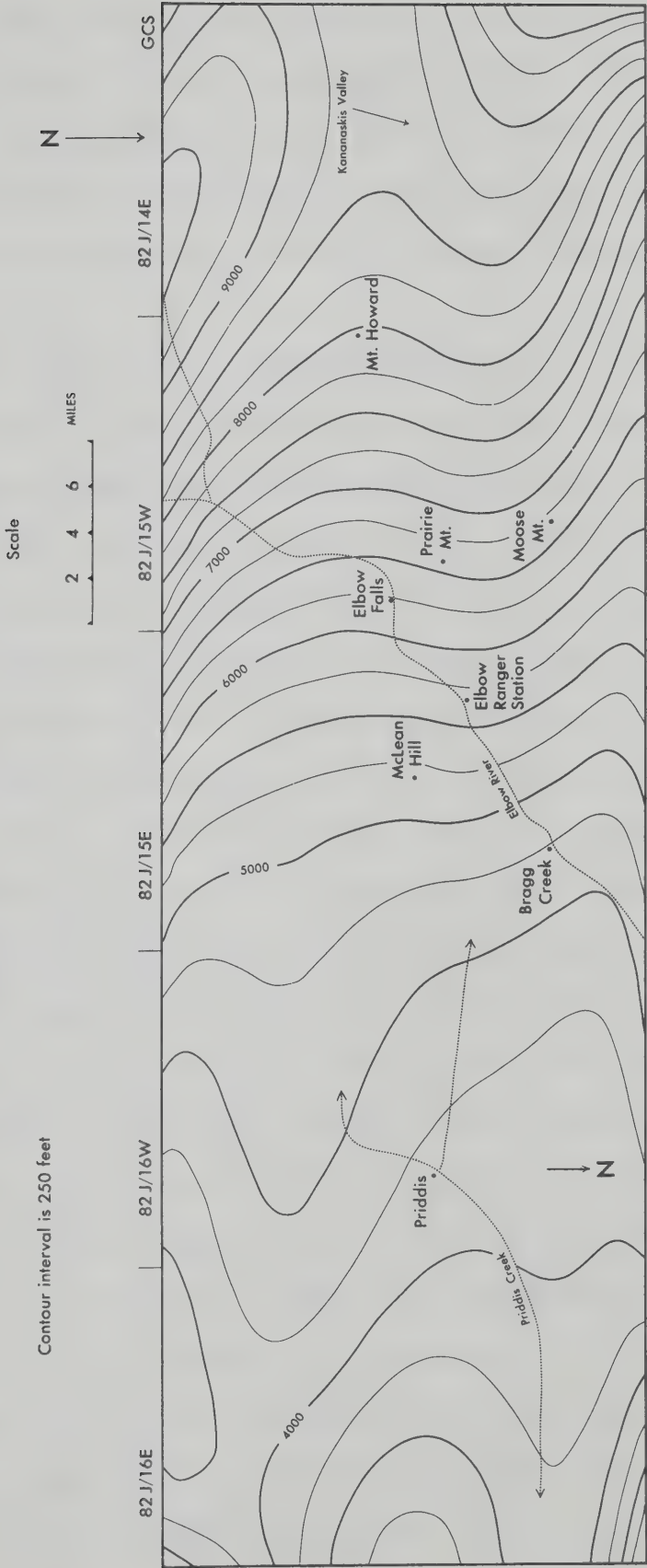
(1) The topography as shown in figure 15, suggests that spatial autocorrelation is present. This means that simple trends of the summit peaks will yield no more

Figure 17

TREND SURFACE MAP OF SUMMIT PEAKS IN THE ELBOW BASIN

SIXTH ORDER SURFACE

Significant at the 99.9% level	94.3
Percentage variance explained	94.3
Standard deviation	433.0
Coefficient of Correlation	0.97



information about highs and lows of the data than that which is already evident, namely increasingly higher values westward from Calgary. Inspection of the 1 through 6 order surfaces showed that only the fourth, fifth and sixth show any recognisable patterns of high and low areas within the general east-west trend.

(2) The high correlation coefficients for all surfaces (Table 6) further supports the assumption of autocorrelation. However, the variation explained, the standard deviation, and the coefficient of determination for the fourth, fifth and sixth order surfaces are all quite close. These statistics for the fourth and fifth order surfaces are very close, whilst the sixth order statistics show a recognisable difference.

(3) All of the surfaces were found to be significant at the greater than 99.9% confidence level. This is thought to be attributed to the large numbers generated for the total variation. The statistics used to find the significance level is the 'F' test, (see appendix 6) where the larger mean square value is divided by the smaller mean square value. In this case if the mean square values are generated from large variation values and there is a large difference between the two sets of degrees of freedom, then since for each surface the numbers of degrees of freedom are fixed, the magnitude of the number of observations will determine how sensitive this form of significance test will be for the analysis in question.

In this study the F value for the sixth order surface was found to be 544.0, and the tabled F value was 1.74 for 30 and

TABLE 6

STATISTICS GENERATED FOR THE TREND SURFACE
ANALYSIS OF SUMMIT PEAK DATA

Order of Surface	1	2	3	4	5	6
Variation Explained by Surface	1247272200.	1305680600.	1322406900.	1346476800.	1348424400.	1353791200.
Variation not Explained by Surface	188482080.	130073620.	113347500.	89277568.	87329824.	81963072.
Total Variation	1435754500.	1435754500.	1435754500.	1435754500.	1435754500.	1435754500.
Standard Deviation	656.74	545.57	509.29	451.99	447.03	433.08
Coefficient of Determination	0.8687	0.9094	0.9211	0.9378	0.9392	0.9429
Coefficient of Correlation	0.9321	0.9536	0.9597	0.9684	0.9691	0.9710

400 degrees of freedom, at the 99.9% level.

(4) The first order surface is accepted as being indicative of a general, regional component in trend surface analysis. In this study the first through fourth order surfaces show similar trends, but very little variation within the surfaces. The fifth order surface contains troughs, whilst still maintaining the trend of the surface. In the sixth order surface these troughs are more distinctive and the general trend of the data is maintained. Since trend and patterns of high and lows of the peaks within the surface are the factors originally assumed to be useful in this study, the sixth order was used to interpret forms evident within the surface.

The Sixth Order Trend Surface

The sixth order surface (Fig. 17) shows increasing elevations westward. The strike of the surface in the central foothills portion of the map is approximately northwest to southeast, and the dip is oriented southwest to northeast. The Elbow River is approximately aligned with the dip, though local changes in direction away from the dip occur. In the eastern part of the map (Fig. 17) the surface indicates the presence of a major valley in this area which begins close to Priddis and extends eastwards. There is a feature which resembles a col in the extreme west of the map (Fig. 17). This col extends westward from Mount Howard, and is therefore located well within the Rocky Mountains. As the trend surface represents major regional trends, according to

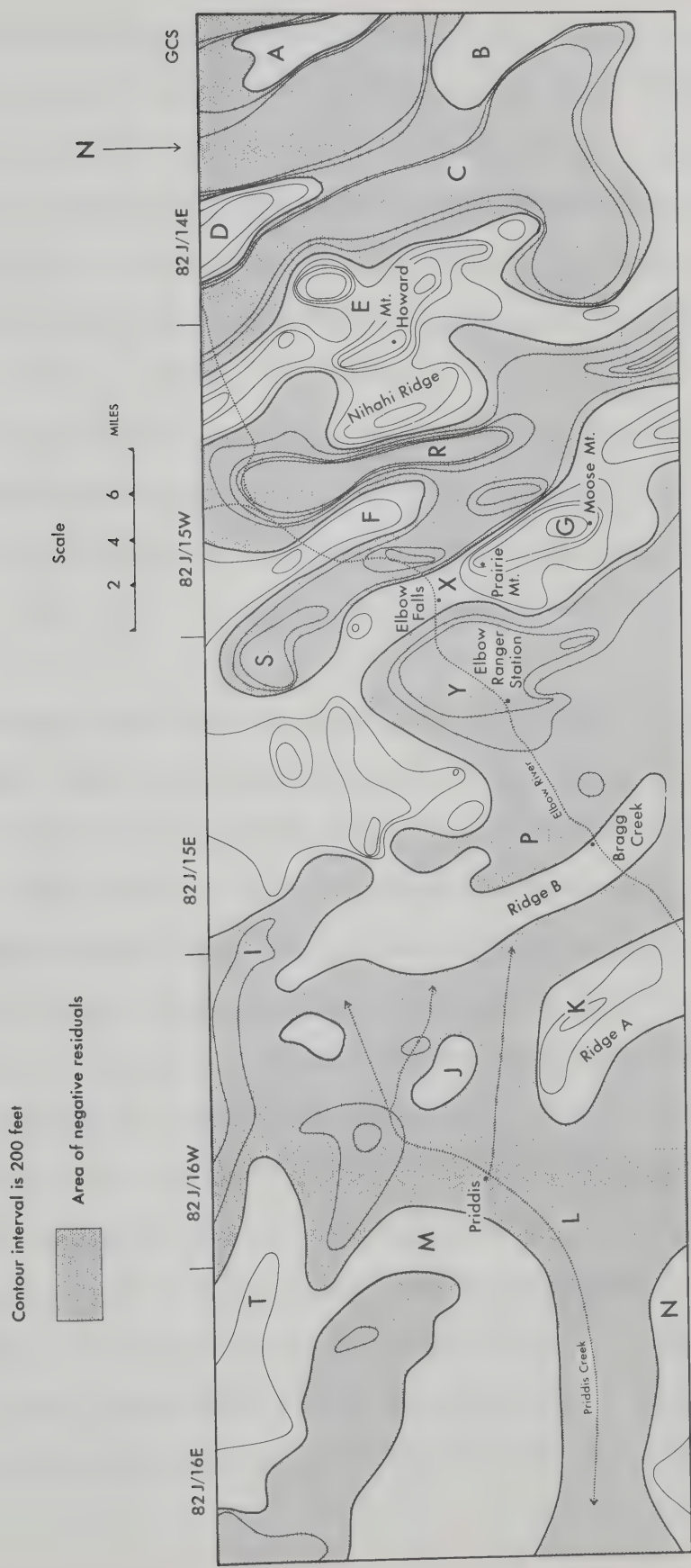
Allen and Krumbein (1962), it is assumed that the feature shown in figure 17 are regional rather than local components of the topography. Hence, the central portion of the map is indicative of the regional topographic components of the foothills. In the case of the Rocky Mountains and the Prairies the size of the sample area is too small in comparison to the dimensions of these two regions, and the trend surface may not therefore be representative of these areas.

The Sixth Order Residuals

The pattern of the residuals plotted and isolined in figure 18, are similar to the isoline map of the raw data (Fig. 16). The letters used to locate features in figure 18, are similarly shown on figure 16. Comparison of these locations will reflect the degree of similarity of the two maps.

To the west of the line north-south through Bragg Creek, the following features are shown similarly on each map (Fig. 16 and 18). The high areas A,B,D, E,F and G. The low areas C,R,S and P. The residual plot (Fig. 18) shows a similar pattern of highs and lows west of a line north-south through Moose Mountain (G), to that of the isoline map (Fig. 16). To the east of this line the pattern is different between the two maps. The relief is lower east of this line on both maps. On the residual plot there is shown a long low ridge trending NNW. to SSE. through Bragg Creek (Fig. 18) which is not found in the isoline map (Fig. 16). To the east of this ridge is the high area marked (K). Between these two ridges there are no data points, which means that there

Figure 18 MAP OF RESIDUALS FROM TREND SURFACE OF SUMMIT PEAKS IN THE ELBOW BASIN
SIXTH ORDER SURFACE



were no clearly identifiable peaks in that area. Hence, the isoline map which tends to produce continuity between points of equal value, shows the area between the ridges as an homogeneous flat area, whilst the effect of the residual plot was to bridge the gap as in a regression analysis. However, both maps may represent this area equally correctly, as both show a low area bounded by a ridge.

To the east of the line north-south through Bragg Creek, the features on the residual map (Fig 18) are less clearly identifiable with the features in the same area on the isoline map (Fig. 16). However, the basic forms are recognisable.

The residual map tends to show that the Elbow River is more discordant with the topography of the summit peaks distribution than does the isoline map. The difference in behaviour of the two types of mapping used above, suggests that this discordance on the residual map is exaggerated. Alternatively, the continuity of form produced by the residual map may indicate an underestimate of the degree of discordance shown on the isoline map. The difference between the discordance shown on each map is that on the residual plot the lines of the discordant features are at right angles to the general line of the river. On the isoline map the discordance is one of the displacement between the valley and the river. Since for Priddis Creek the river and valley are accordant on both maps, two types of discordance of the Elbow River may exist.

Summary of the Topographic Analysis

In terms of the interpretative qualities of each of the two techniques used, isoline mapping of the summit peaks was more reliable. The doubts concerning the trend surface analysis centres upon statistical fitting of the regressed surface and the degree of generalisation achieved. As relief decreases the behaviour of the polynomial fit appears to vary more than in the case of the isoline map. The trend surface analysis produces greater continuity of form in high relief areas, whilst the isoline map reflects smaller and more local features in similar areas.

There is reason to believe that an older surface of erosion may have existed, for the following reasons.

The trend surface (Fig. 17) shows an accordance of the present Elbow River with the dip of a surface which has a high degree of correlation with the summit peak data.

The topography of the foothills is strongly influenced by geological structure. The Elbow River is discordant with geological structure, and also with the pre-Pleistocene topography in the foothills. To the west of the Elbow River, the author has noticed a greater accordance of rivers with structure, as for example in the Kananaskis valley. To the east of the foothills in the Elbow basin the topography is less dependent upon geological structure and the rivers show a greater accordance with the topography of the summit peaks.

A point of explanation concerning the discordance of the Elbow River in the foothills downstream of point (Y) in

figure 16, is that below this point the Elbow valley has a thick surficial infill of gravels and till. The asymmetry of the river in the valley shown in figure 16 may therefore be due to glacial interference. This point will be discussed further in chapter 4. Hence, the residual map may reflect the major form of discordance between the present river and the topography.

A final point is that approximately fifteen miles west of the headwaters of the present Elbow River is the continental divide.

Conclusions for the Topographic Analysis

There was no sedimentary cover which extended uniformly over the whole study area and its environs, and three basic structural and topographic units are evident. These are;

The Rocky Mountains, east of the continental divide and west of Nihahi Ridge (Fig. 19, east of region 1).

The foothills, east of Nihahi Ridge and west of a line north-south through Bragg Creek (Fig. 19, regions 1 and 2).

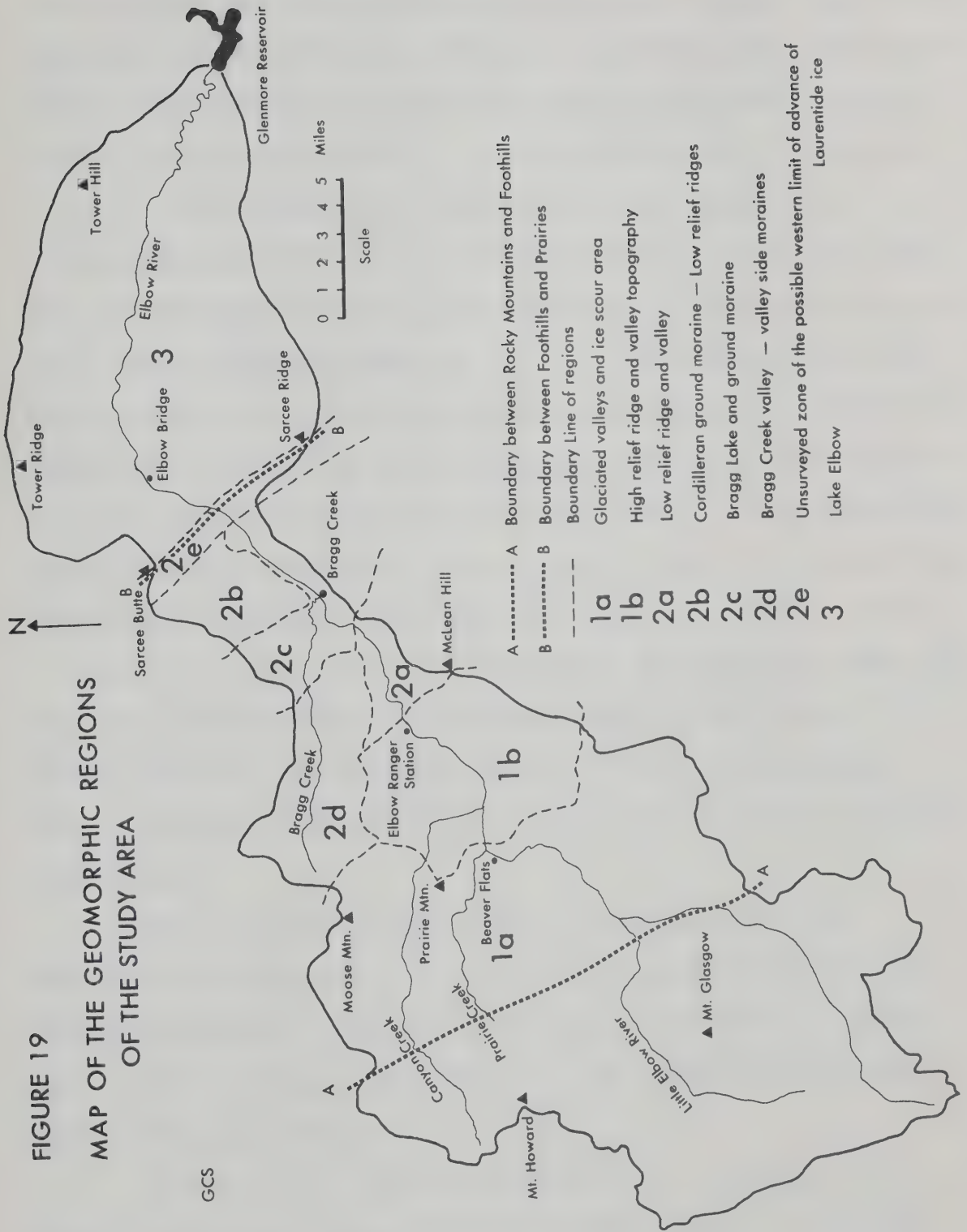
The Alberta Prairie region, east of Bragg Creek (Fig. 19, region 3).

Interpretation of the Tertiary Geomorphic History of the Elbow Basin and Environs

The end of the late Cretaceous period was marked by a marine recession from the vicinity of the study area. In

FIGURE 19

MAP OF THE GEOMORPHIC REGIONS
OF THE STUDY AREA



other local areas of Alberta marine sedimentation continued. Tozer (1956) described marine sediments at several localities along the Prairie-foothills margin, but noted that the contact between the Edmonton and Paskapoo formations showed a marked break in the Elbow basin, ". . . 10 miles south of Cochrane" The Paskapoo at this basal level consists of ". . . conglomeratic beds. . . . On Elbow River a large bone fragment, presumably dinosaur, was collected 80 feet stratigraphically above this conglomerate" No shales have been found, which suggests that recession and subsequent sub-aerial deposition occurred in the Paleocene. Prior to this recession the late Cretaceous marine environment had not been extensive, and the western margin of the sea was in the vicinity of the foothills of Alberta (McCrossan and Glaister, 1964). Hence, a sub-aerial environment had existed in the area now known as the Rocky Mountains and the western edge of the Alberta foothills, prior to the Tertiary period. Thus, in Paleocene times sub-aerial denudation and deposition extended over the study area.

The Laramide orogeny began in mid-Eocene times (McCrossan and Glaister, 1964) and continued throughout the Oligocene period. Minor earth movements occurred in Miocene times and the orogeny culminated in one last phase of movement in Pliocene times.

A sub-aerial environment persisted throughout the Eocene, Oligocene, Miocene and Pliocene periods. Westgate (1965), working in the Cypress Hills of southeast Alberta,

associated the upland surface of this area with a long period of sub-aerial denudation which lasted from mid-Paleocene times until the end of the Tertiary era. Crickmay (1965) postulated panplanation, a process of lateral planation by rivers, (Crickmay, 1933) as the cause of the flat surface. It was also suggested that by this process and late Tertiary rejuvenation the Cypress Hills became an isolated upland area. The Cypress Hills are on the eastern flank of the late Cretaceous-Paleocene "Alberta Syncline." The Elbow basin is on the western margin of this syncline. Therefore, it is expected that drainage flowed toward this synclinal area in southern-central Alberta.

Conclusion: The Pre-Pleistocene Evolution
of the Elbow River

In the study area two pre-glacial valleys are identified. One is in the Prairie region (Priddis Creek valley) and the other in the foothills (Elbow River valley). Neither of these valleys can be traced across the foothills/Prairie boundary. The presence of a pre-glacial valley and a Paleocene river in the foothills, both of which approximate the direction of the present valley of the Elbow River, suggests that the Elbow River was antecedent to geological structures formed during Eocene and Oligocene times. The present dependence of topography on geologic structure in the foothills of the study area may further support this hypothesis. However, without more conclusive evidence within the study area of benches which may only be attributed to antecedence,

this hypothesis remains conjectural.

An alternative explanation may be that of post-Laramide superimposition from a peneplain. In this case the assumption is that during Eocene and Oligocene times, topographic forms created by orogenic disturbances and pre-Laramide topography were reduced to a peneplain by the beginning of Miocene time. This peneplain may be reflected in the highly correlated summit peaks found in the trend surface (Fig. 17). Subsequent rejuvenation of drainage during Miocene and Pliocene times may have been caused by earth movements along the 'Disturbed Belt,' as mentioned by Tozer (1956). Hence, superimposition of late Oligocene/early Miocene drainage patterns may have taken place. A similar process is described by Westgate (1965) for the Cypress Hills, in SW. Alberta.

In order to substantiate either one of these hypotheses two types of information are required. The first concerns more detailed investigation of surface and bedrock topographies in order to accept or reject the hypothesis of antecedence. If the hypothesis of antecedence is rejected, then a second source of information is required to substantiate the hypothesis of superimposition. This would involve a search for clastic sediments which may be attributed to the peneplanation stage of the Laramide geologic structures prior to possible superimposition in Miocene and Pliocene times.

Post Tertiary Geomorphic History of the Elbow Basin

The uncertainty of events within the Tertiary era of

Alberta appears to carry through into the Pliestocene era. Despite extensive glaciers over North America during the four major glaciations attributable to North America only the last, the Wisconsin, is discussed for Alberta with any certainty (Stalker, 1960).

The pre-Wisconsin landscape was modified by Cordilleran and Laurentide ice masses and associated deposits. The extent of the modification and/or change which took place is not clear, since knowledge of the pre-Wisconsin landscape is vague. The amount of change due to Wisconsin ice alone is difficult to assess in the light of a possible earlier glaciation of the study area.

Morphology and the Surficial Sediments

The study is considered in three regions in this section.

- (i) West of McLean Hill.
- (ii) East of McLean Hill and within the foothill region.
- (iii) East of Elbow Bridge.

(i) The first area (1B) is west of a north-south line through McLean Hill (Fig. 19). This area has the greater relief, and evidence of glacial erosion. In figure 20 the major morphological forms have been mapped using field observations and aerial photographs. In order to illustrate differences in the morphology of the study area, the mapped area of figure 20 has been extended westward as far as Mount Glasgow.

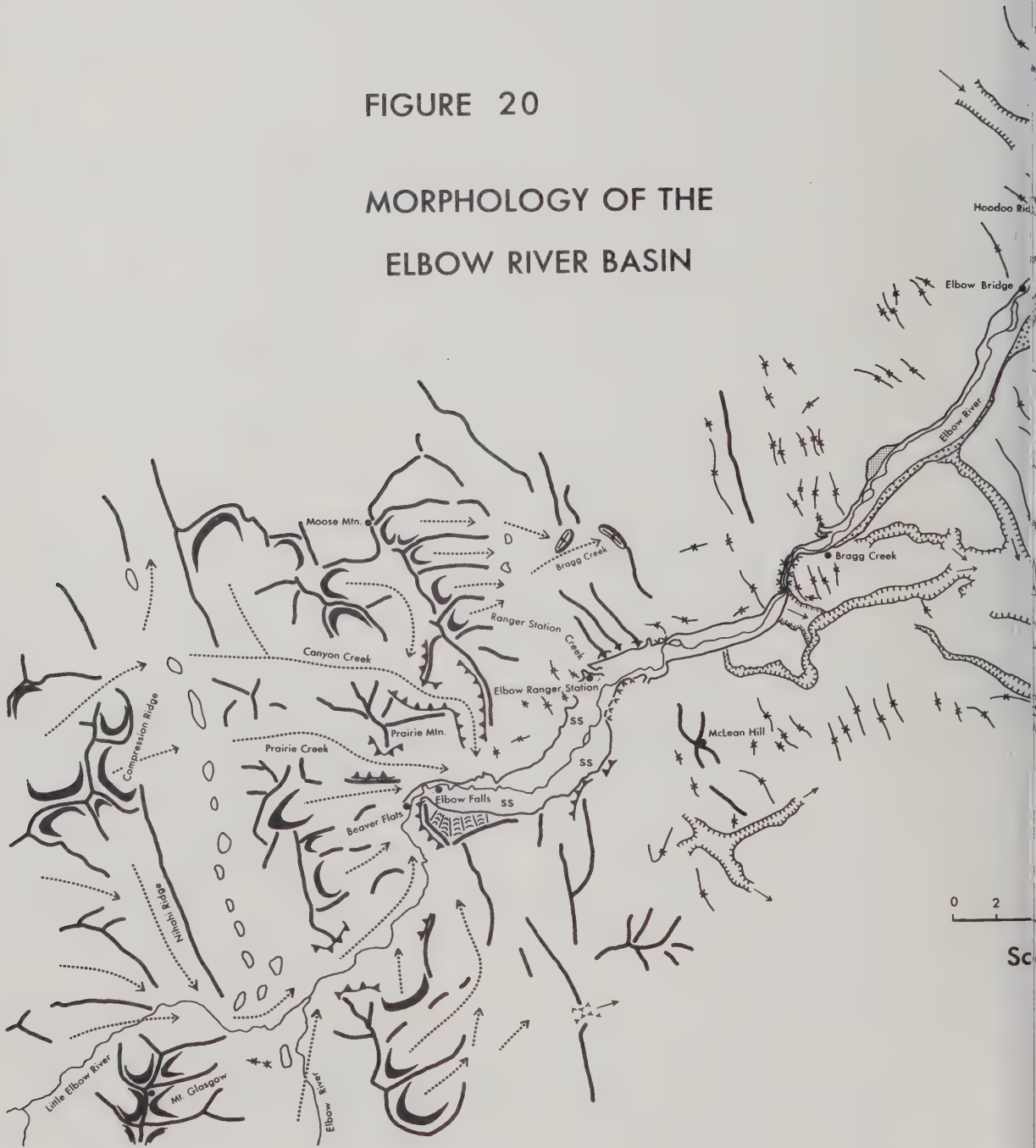
A prominent morphological feature is the concentration of cirque forms in the higher relief areas close to and west

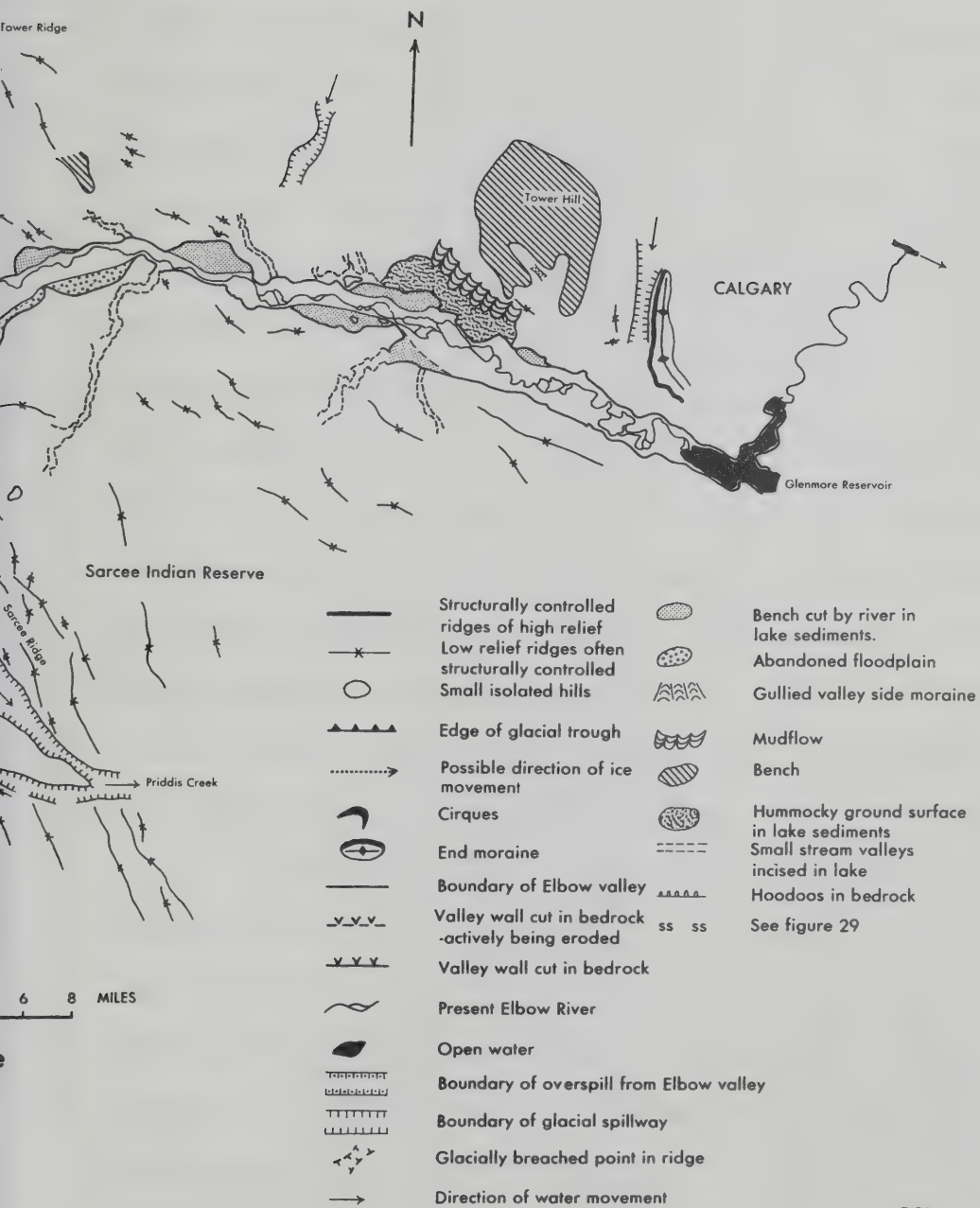
of Moose Mountain (Region 1A and Westwards; Fig. 19). A second prominent feature is the extensive and high relief ridges which controlled ice movement. To the west of Elbow Falls the valleys are typically 'U' shaped with valley side moraines extending well above the valley floors. Within this area are three main cirque locations. (1) Forgetmenot mountain, (2) Mount Glasgow and west of Nihahi Ridge, and (3) around Moose and Jumpingpound Mountains (Fig. 20). Since ice probably did not spill over into the Elbow system from the Kananaskis valley (Pers. Comm. Mr. M. Walker, University of Calgary), the above were the source areas of Cordilleran ice which occupied the Elbow valley in Wisconsin times. The main directions of ice movement proposed are shown in figure 20. The movement of ice across the broad valley immediately east of Nihahi and Compression Ridge may be attributable to ice blocking at the north end by Bow and Kananaskis ice, as well as the pre-existence of river valleys which traversed east via Canyon and Prairie Creeks, and via the Elbow and Little Elbow valleys (Fig. 20). Therefore, the ice would probably have been thickest close to Elbow Falls, because at this point most of the ice from all sources was confined in a narrow valley.

East of this point (in region 1B; Fig. 19) the main valley is broad and occupied by fluvial sediments varying from 50 to 150 feet thick. The valley walls consist of truncated spurs which show evidence of glacial action, and low interfluvial areas with adjacent valleys. Till is

FIGURE 20

MORPHOLOGY OF THE
ELBOW RIVER BASIN





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restricted to valley sides and is rarely exposed from beneath lake or fluvial sediments. On the valley sides of this region the thin surficial cover is strongly influenced by local bedrock. This suggests that the surficial material in these areas may be mass movement debris, developed under periglacial conditions on the hills peripheral to the main valley, rather than till. Further research into this problem would be necessary to determine whether this material is weathered bedrock, or weathered and/or disturbed till. Evidence of intensive periglacial action was found on Tower Hill (Plate 4). Almost all of the northwest to southeast oriented valleys of the interfluvial areas of the basin are presently occupied by bogs, with up to 30 feet of fine clay and gravels. The scarcity of sections in till and the poor quality of exposures found leaves questions about flow directions and the extent of ice cover in the area unanswered. The fluvial environment of this part of the study area will be considered in Chapter 4.

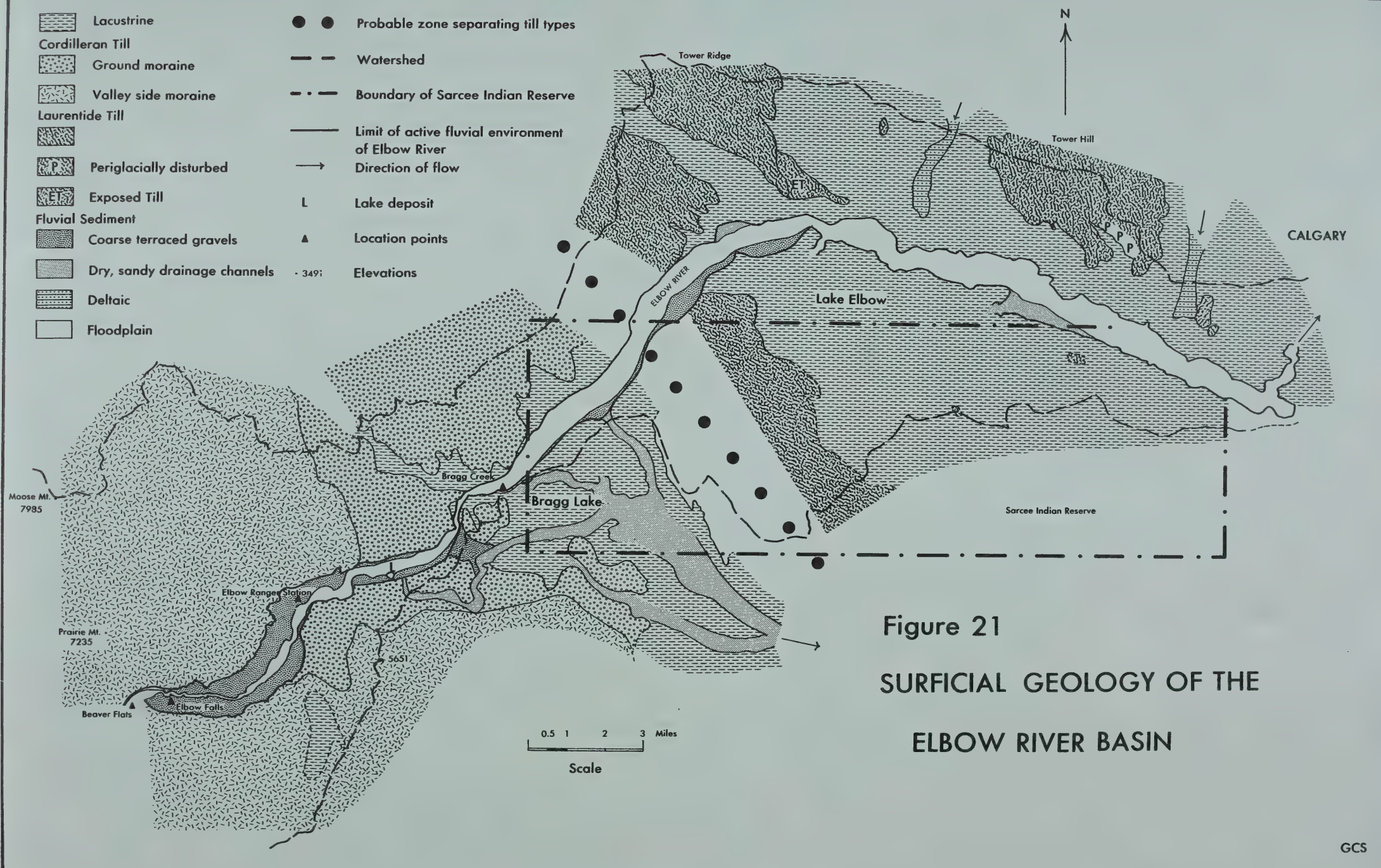
(ii) The second area is bounded by north-south lines through McLean Hill and Elbow Bridge (Fig. 20). This area is most difficult to describe. The findings about this central region of the study area have shown that it is complex. The form of the complexities reveal the inadequacy of the data collected for a full description of the area both spatially and temporally. The basic form of the problem concerns boundary zones or limits. One such limit was considered in the first part of this chapter, namely the Prairie-foothills boundary zone. Others include the western limit of advance

of Laurentide ice (Fig. 21), the distinction between two lacustrine areas, and the limit of advance of Cordilleran ice.

The area is dominated by northwest to southeast ridge and valley forms to the north of Bragg Creek (river) and south of the Elbow River. Therefore, this area is considered in five units, with the Elbow valley considered in Chapter 4.

(ii-a) The southern area (Region 2A; Fig. 19) of ridge and valley is lower in relief than similar topography further west. The composition of material covering these slopes is similar to that described on the valley sides in area (1) where the true identity of the material was in doubt.

(ii-b) The ridge and valley topography to the north of Bragg Creek town site (Region 2B; Fig. 19) is not as intense as that found south of the Elbow River, and tills are more clearly identifiable. Valley bottoms are often covered with 2 to 6 feet of lake sediment with till exposed on spurs and flanking ridge slopes. To the north of Bragg Creek town site samples of till were taken and originally described as Cordilleran in origin. A transect from headwaters to confluence of Bragg Creek (river) had shown that a small local Cordilleran glacier occupied this valley and the tills north of Bragg Creek town site were thought to be due to Bragg Creek ice and Elbow ice jointly. However, the sediment analysis revealed that these tills were not distinctly Cordilleran in type. Since the clay-silt fraction was higher,



there is a possibility that the samples involved are from Laurentide till. However, throughout the ridge and valley regions and within Bragg Creek valley the influence of bedrock was strong. In this area north of Bragg Creek town site the bedrock is largely Upper Alberta formation which consists mostly of soft shale and some sandstone. Thus, without further detailed petrographic, mineralogical and fabric orientation data, it was not possible to substantiate the Laurentide origin. Morgan (1966) and Nichols (1931) both described Jumpingpound till in this vicinity as Cordilleran. Nichols (1931) made the suggestion that this till was attributable specifically to Jumpingpound Ice. Yet inspection of the Jumpingpound basin reveals few ice source areas. Therefore, the supposition by Morgan (1966) that Kananaskis and Bow Valley ice spread south, over and beyond Morley Flats into the Jumpingpound area seems more feasible. In addition researchers from the Calgary base of the Geological Survey of Canada (Pers. comm. Dr. N. Rutter) have identified morainic forms which are flute-like, and traverse the ridge and valley topography of the Jumpingpound basin. These were termed flutes but may be ablation moraines attributable to melting Bow Valley ice.

(ii-c) The lacustrine and ground moraines of the area peripheral to Bragg Creek town site and extending west and south along the Elbow valley define the third area (Region 2C; Fig. 19).

All samples from this lake area had greater than

98.5% clay-silt. The upper elevation of the lake was determined as 3975 feet (the highest elevation at which lacustrine samples were found) and the extent of the lake mapped on this basis. This lake will hereafter be referred to as Bragg Lake. The southern part of Bragg Lake south of the Elbow River is dissected by wide, shallow, dry and flat bottomed channels which suggests drainage of Bragg Lake to the south east through gaps in Sarcee Ridge (Fig. 20). One such gap is over 500 feet in total relief and presently carries Priddis Creek. The broad, flat lake area bordered by ground moraine to the south, Sarcee Ridge to the east, and Last Break Hill till area to the north, would seem a feasible pre-glacial drainage route for the Elbow River. However, the present Elbow River does not take this course but cuts the topographic divide between Bragg Creek valley and the Elbow valley at a point 1-1/2 miles southwest of Bragg Creek town site (Fig. 17). The small northwest to southeast oriented valleys east of this point are blocked off on the south side by the low moraine traceable to the west for one-half of one mile. The Elbow river has breached this moraine on the upstream limit of Bragg Creek, whilst an isolated, flat, gravel terrace is traceable between the present Elbow valley and Bragg Lake. The terraced gravels are weathered, covered by Mazama ash and lack good exposures for estimating fabric orientation. Imbricate structure shown by pebbles in a sand lens, however, indicated flow to the east, directly into one of the dry drainage channels of Bragg Lake which led to Priddis Creek.

(ii-d) A transect along the forestry road in Bragg Creek valley (Region 2D; Fig. 19) revealed a broad, flat floored valley with deep morainic infill, and several small truncated spurs. This suggested erosion as well as deposition by glacier ice, the source of which must have been in the valley headwaters along the eastern flanks of Moose Mountain Dome. End-moraines were traceable down valley to one mile east of the forest boundary (Fig. 20). At this point ground moraines and lake sediments were encountered as relief became low in the lower Bragg Creek basin. Immediately downstream of each end-moraine medium to coarse gravels were found, not terraced, with no imbrication, and which directly overlay bedrock (Plate 5). These gravels were assumed to be outwash gravels. North of the Ranger Station Creek (Fig. 20) in Bragg Creek valley, are extensive sloughs occupied by lake sediments and coarse gravels. The lake sediment uphold active bogs. It is thought that these sloughs represent a phase of outwash of gravels developed during the final retreat of ice from this basin. In the lower Bragg Creek basin, the creek has incised deeply into lake sediments and ground moraine (Cordilleran) creating widespread and recently active slump features (Plate 6).

(ii-e) Finally, the eastern part (Region 2E; Fig. 19) of this central study area, which also forms the western limit of area 3 (below and Fig. 19), is a zone not sampled in the vicinity of the Sarcee Indian Reserve. It is an area dominated by Sarcee Butte to the north and Sarcee Ridge to



PLATE 6

Shows slumping of lacustrine clays at site 131, near Bragg Creek.



PLATE 7

Shows banded lacustrine sediments overlying till (lower right corner) at Elbow Bridge (Site 11 and 79).

the south of the Elbow river. To the east of this zone Laurentide tills were identified, whilst to the west Cordilleran tills were found. To the east is an extensive lacustrine area at a lower elevation than Bragg Lake to the west. The degree to which each of the Cordilleran and Laurentide Ice masses encroached upon this zone is not certain.

(iii) This area includes all of the study area east of the Elbow Bridge. At sites 11 and 79 lake sediments were sampled which overlay till in the manner shown in figure 22 (Plate 7). The lake sediments are of the lower lake, herein called Lake Elbow, (although in fact an extension of Glacial Lake, Calgary, (Morgan, 1966). The till appeared to be Laurentide in origin, as were tills half a mile north (Fig. 21). These particular till samples fell in the Laurentide-Cordilleran till overlap of the factor loading lists. Although phase two of the analysis, between the two tills, designated the samples from the above sites as Cordilleran the initial designation is maintained, because of bedrock influences. This is because Bearpaw sandstones are exposed locally and are easily eroded, and may therefore have contributed coarser material to the tills of this area. Close to Hoodoo Ridge in two till sites, granitic pebbles were found which further supported the original designation. To the east of these sites Laurentide till is exposed on the higher elevations above 4000 - 4100 feet (Fig. 21). Below this level are lacustrine deposits of Lake Elbow.

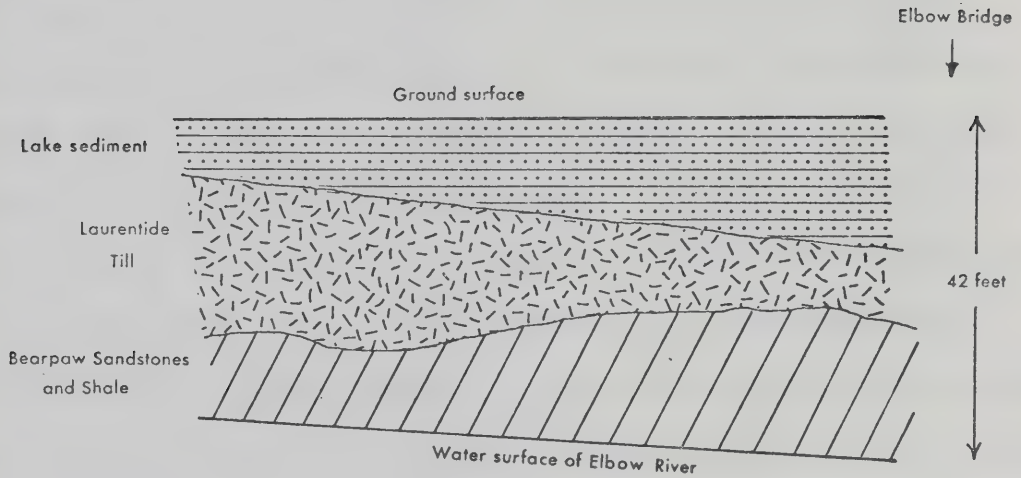


FIGURE 22

CLIFF SECTION AT ELBOW BRIDGE

Shows lake sediments from Lake Elbow overlying Laurentide till.

The lake sediments are varved (Plate 17) in the top 4 feet, and contains buffalo bones.

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The analysis of the Laurentide tills in phase three (components two and four, Fig. 12), suggested two groups of this type. The interpretation of the values for each site did not, however, produce any understandable relationships between the values. This would concur with Morgan (1966), who described all Laurentide till in the Elbow basin as Erratics Train Ground Moraine. On the other hand the complexity of till types described by Tharin (1960) cannot be envisaged as occurring in this area. In the vicinity of Tower Hill to the west of Calgary, evidence of complexities of till structure was found. Tower Hill, which has long smooth convexo-concave slopes on the south side and an extensive, flat, very gently dipping eastern summit (of less than one degree) (Fig. 20), is everywhere covered by till, except on the upper southwest slopes where mass movement has exposed bedrock. In addition, in the benched part of the hill, above the lake sediments, periglacial features are common (Plate 8), with ball clays (Plate 9) and ice wedges which penetrate bedrock (Plate 10). It cannot be conceived that the bench, cut in till and presently dissected by deep misfit river channels, is due to a periglacial cycle of erosion such as described by Peltier (1950). The till cover precludes pre-Wisconsin formation. One suggestion would be the action of Glacial Lake Calgary. However, this would require the Lake Elbow sediments be found up to 4050 feet. In fact lake sediments were only found up to 3975 feet, which may indicate mass wasting in the inter-fluve areas over 3975 feet. A similar bench is found southeast of



PLATE 8

Ice wedge in pebbly till on Tower Hill at site 24. Gravels underlay the till in the gap at the base of the photograph.



PLATE 9

Shows what may be a ball clay. The material is till in the same section as above, on Tower Hill.



PLATE 10

Site 51, on Tower Hill.
Ice wedge penetrates
bedrock in lower third
of photograph. The
surficial material is
till.



PLATE 11

Shows bench in the centre horizon, with two stands of trees
on it. Location is on a S.E. extending ridge from Tower
Ridge.

Tower Ridge (Plate 11) projecting into the lake region at the 4000 foot level. To the east and west of Tower Hill are overflow channels at 3725 feet and 3870 feet respectively. In each case deltas are built up on the south side indicating overspill from the Bow valley into Lake Elbow at two different time periods. To the east of Tower Hill and interbedded with the delta on the east side, is till which forms a notable north to south ridge. This is thought to be an end moraine. The land elevation to the south of the Elbow in this part of the study area is generally below the 4000 foot level.

Conclusion for the Post Tertiary Geomorphic History of the Elbow Basin

The conclusion pertaining to the possible sequence of events in this area are now presented.

Preliminary investigations suggest Laurentide ice advanced as far west as Sarcee Butte and Sarcee Ridge. At this time, Bragg Lake was formed as the Priddis Creek gap and the present Elbow Valley were blocked off. Subsequent retreat of Laurentide ice in a north-east direction allowed Bragg Lake to drain south-east through Priddis Creek before increased volumes of meltwater eventually cut the present course. The Laurentide ice front must have been extensive, and when it was in retreat meltwaters formed in increasingly extensive ice front lake - Glacial Lake Calgary. Subsequently, Laurentide ice either re-advanced or stagnated on the eastern flanks of Tower Hill. The lake level rose to approximately 4050 feet when the two benches (Fig. 20) were cut in ground

moraine. With continued retreat the lake level dropped as water drained either directly south or through the present Elbow valley south of Tower Hill. Exposure of the benched areas in a lake environment created intense periglacial action. This lake sediment, deposited on high interfluvial areas, was washed off and till exposed as water drained away (Fig. 21). This would explain why lake sediments are not found up to 4050 feet. As the Elbow - Bow valley watershed was exposed overspill from the Bow cut the higher spillway (Fig. 23). The continued stagnation of Laurentide ice and a drop in lake levels created Lake Elbow, until eventually water drained south again on the east flank of Tower Hill. A minor advance is illustrated in Figure 24, where till overlays disturbed gravels and is overlain in turn by very coarse and massive bedded deltaic gravels (Plate 12 and 13). Subsequently, the lakes were completely drained as ice retreated again. A paleo-soil found close to the delta (Plates 14 and 15) could not be interpreted without further information from within the vicinity. However, the following additional points are relevant to the conclusion.

(i) The lake Elbow sediments contain many pebbles which were probably ice rafted into the area.

(ii) Buffalo bones were found in the top 18 to 24 inches of the lake sediments, indicating a prolonged phase of existence of Lake Elbow as a distinct lake when 'life' could return to the area. In addition, it would place the final retreat of the ice within very late Wisconsin times.

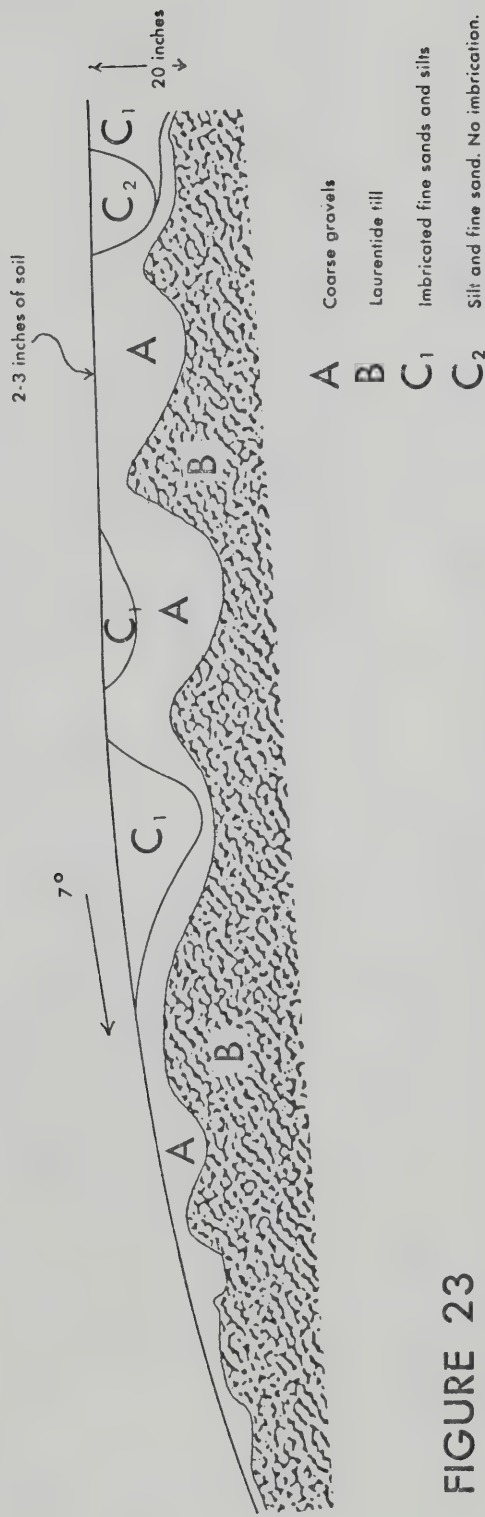


FIGURE 23

SKETCH FROM SITE 36

On east flanking slope of spillway near delta to the west of Tower Hill

The section is close to the floor of the spillway. The distortions in the till and in the coarse gravels are small lateral scour channels.

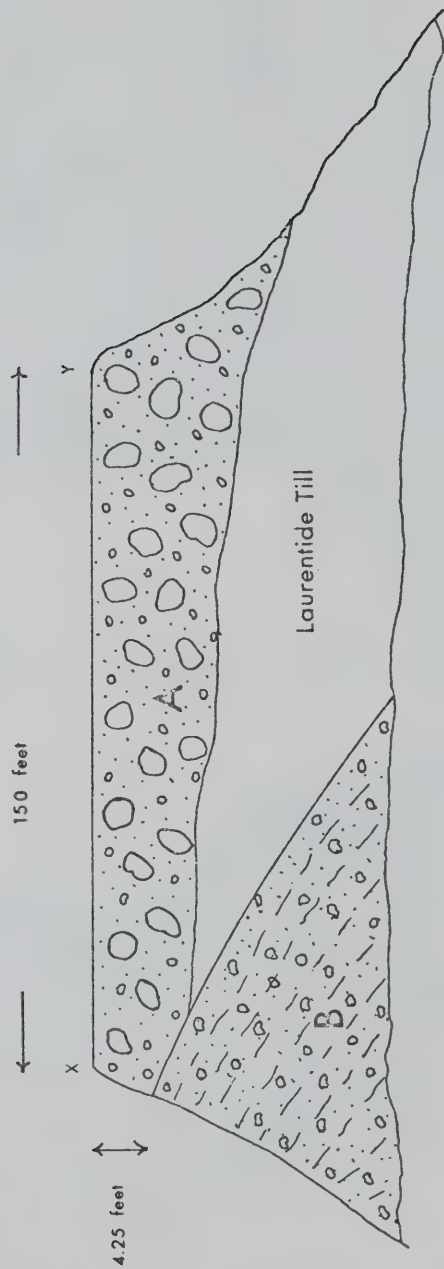


FIGURE 24

SKETCH OF SECTION IN DELTA ON EAST SIDE OF TOWER HILL

X — Y indicates a direction WNW to ESE

A Gravels as shown in plates 12 and 13

B Medium coarse gravels with bedding as shown

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PLATE 12

These gravels are deltaic. There is no visible imbrication. The sides of the square are each one foot in length. The section is found at McPherson's Quarry, just west of site 25, in S.W. Calgary.



PLATE 13

Shows till enclosed in gravels which form part of the delta at site 25. The road is Sarcee Road in S.W. Calgary.



PLATE 14

Paleo-soil buried by mass waste material near site 25.

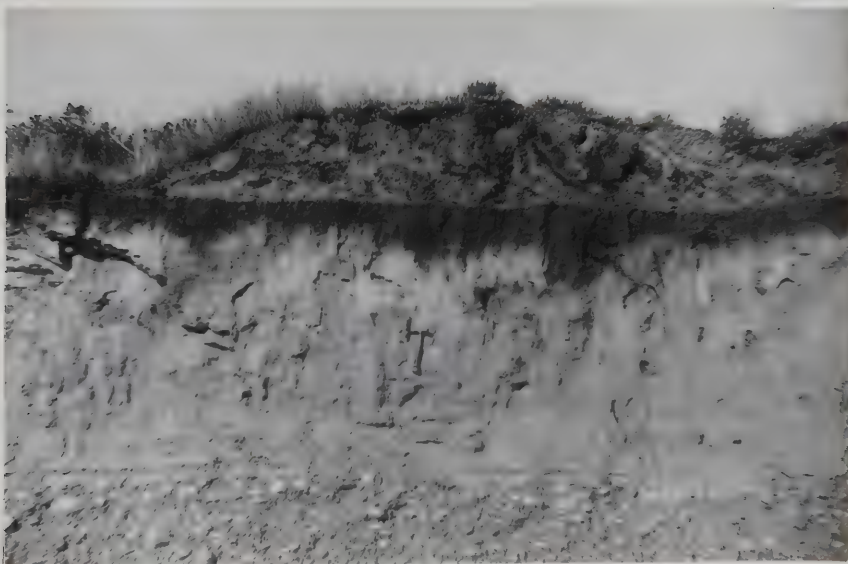


PLATE 15

Continuation of the paleo-soil shown in plate 14, with lacustrine sediments overlying gravels.

(iii) The lack of sediments above 3900 feet is due to two factors. The first is that the interfluve areas are barely above this elevation, and hence deposition of material in these areas would be limited. Secondly, in the high relief areas around Tower Hill mass movement is evident. The proposed type of movement is by mudflow, as a section taken at 3874 feet at site 41 (Fig. 25 and Plate 16) shows overlapping shallow channels on a 15 degree slope in very fine clay material. This would also explain local, very stony patches of till in which the clay-silt content was low (around 30% to 40%) for Laurentide till. Mass movement by soil creep is held responsible for exposing till around Tower Ridge.

(iv) The form of the bench on Tower Hill suggests very shallow water. This is the only place a shoreline may be located. Elsewhere, the drop in lake level must have been fairly rapid. The misfit valleys of Tower Hill may also be accounted for by lake levels which covered the bench on which they are found.

The chronology pertaining to the Cordilleran ice was indeterminable on the basis of data collected. The relationships of the post-glacial environment in the Elbow River will be discussed in Chapter four.

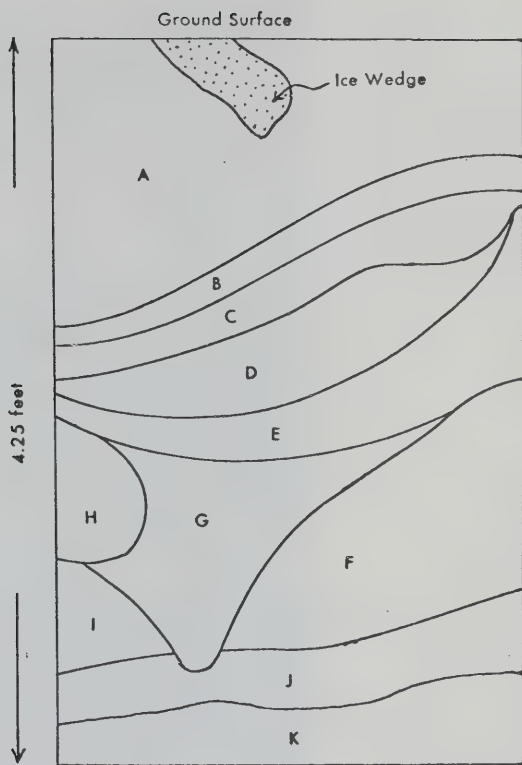


FIGURE 25

SKETCH OF SECTION SHOWN IN PLATE 16

The section is cut on a concave lower slope on the S.W. side of Tower Hill.

- A Silt and clay
- B Dark grey clay
- C Silt
- D Sand and clay
- E Silt and clay
- F Dark clay
- G Silt, clay and sand
- H Fine sand, silt and clay
- I Dark clay with pebbles up to 8mm
- J Silts, sands and gravels
- K Clay



PLATE 16

Site 40. Mudflow patterns are partly discernable in a clay rich material (probably lacustrine) containing thin bands of small pebbles.



PLATE 17

Photograph of fossils collected from lacustrine sediments at site 6, at Connop Creek.

CHAPTER IV

THE ELBOW RIVER AND VALLEY

The behaviour of the Elbow River within the present valley is discussed in this chapter. The time period studied is from late Wisconsin times to the present.

The upstream section of the Elbow valley is dominated by bedrock constrictions between which are numerous unpaired terraces. This was established from approximate altimetric measurements of all the major terraced surfaces upstream of Bragg Creek, taken from aerial photographs at the 1:2640 scale. South of the river and above the highest terraces the land is relatively flat where ground moraines border the fluvial debris. In the downstream section the valley is cut in lake sediments. Bedrock is rarely exposed, and no terraces are found. Occasionally the river has cut benches in the lake sediments. The point of change between the two sections is near Bragg Creek town site.

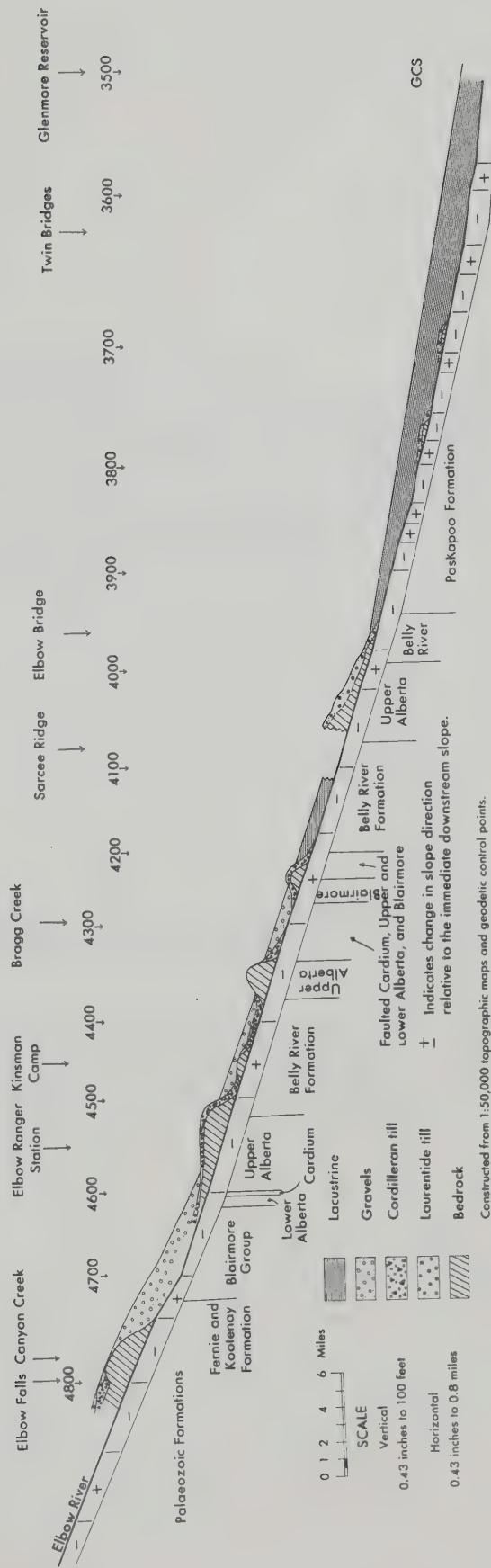
The Elbow River Upstream of Bragg Creek

Upstream from the road bridge at Bragg Creek the behaviour of the Elbow River is subject to bedrock control in two ways. The first concerns constriction of the valley where bedrock outcrops in the valley side, thereby restricting the continuity of the river pattern within the floodplain.

The second bedrock control concerns the exposure of bedrock in the side of the channel. Associated with each bedrock control is a local steepening of the channel gradient, except at the bedrock outcrop immediately upstream of Bragg Creek (at the Provincial Park). In most cases, the steep gradient is found in the region of the outcrop or on the upstream side (Fig. 26). This would suggest progressive headward retreat and the removal of the influence of each local bedrock base level. At the same time, the majority of these points continue to influence the slope of the river. The exception is found upstream of Bragg Creek at the Provincial Park (Fig. 2) constriction. In this case, soft carbonaceous shales of the Upper Alberta formation have been more rapidly eroded, such that adjustment of slope to the downstream local base level at the road bridge in Bragg Creek is now taking place. The bedrock is very close to the surface in the Provincial Park constriction, but the river has aggraded sufficiently to produce a braided channel. The aggradation is thought to be quite recent.

The reaches between each constriction upstream of the Provincial Park are incised into thick deposits of coarse fluvial material. In some cases lacustrine and/or till deposits are exposed in the valley side beneath the fluvial material (Fig. 26). One such occurrence is shown in Figure 27, at Connop Creek. In this case a collection of small fossils were found in clay rich lake sediments, consisting of gastropods and occasionally brachiopods

FIGURE 26 LONGITUDINAL PROFILE OF THE ELBOW RIVER WITHIN THE STUDY AREA



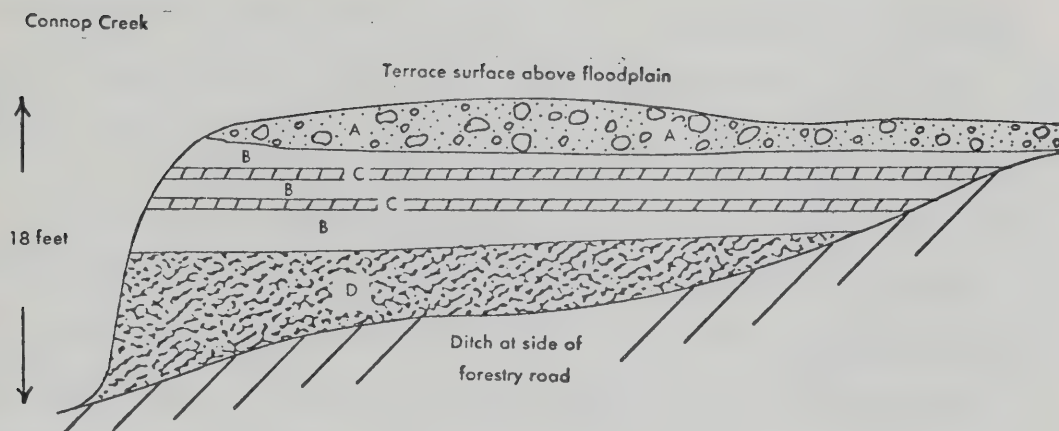


FIGURE 27

ROAD CUT SECTION AT CONNOP CREEK

Shows coarse fluvial gravels (A) overlying lake sediments (B and C). The till (D) is Cordilleran. The lake sediments are part of a small local lake and are varved. The thin bands (C) are black, clay rich and contain small fossils (Plate 17)

GCS

(Plate 17). Another site at which similar fossils were collected was found at the top of the gorge 300 yards west of Canyon Creek. In this case lake sediments largely composed of silt and fine sand overlay till and bedrock. At another site half a mile east of the Kinsman Camp constriction, at site 83 (Fig. 2), evidence of at least one re-advance of the Elbow valley ice was found (Fig. 28). The section is taken from a 50 foot river cliff on the south side of the floodplain in which erosion at the cliff base has caused slumping of the cliff. The till, overlain on the west side by fluvial gravels, and overlaying gravels on the east side, contain a large number of well rounded pebbles (Plate 18). This suggests that the buried and disturbed gravels represent a phase of outwash prior to re-advance of the ice.

Despite the above localized complexities of the stratigraphy of the upstream section of the Elbow River, there is one unifying factor. The coarse gravels associated with the highest terraces have buried or replaced most of the earlier deposits. The same gravels are characterized by the lack of stratification. Sand lenses (Plate 20) are common, and a few pebble orientation fabrics taken vary in direction and strength of the major orientation. The uniformity of the material found within the terraces is striking (Plate 19). Grain sizes range in excess of 256mm, and boulders up to 18 inches are not uncommon. As shown in Fig. 9, the percentage finer than 0.063mm is small. The

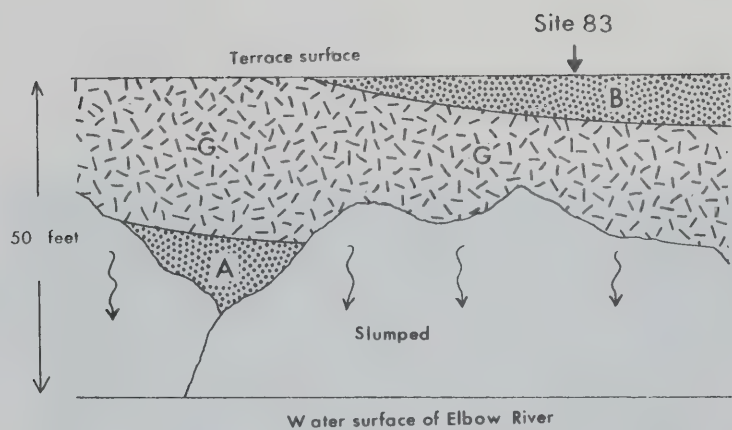


FIGURE 28

SKETCH OF SECTION IN RIVER CLIFF
AT SITE 83

Shows till G overlying disturbed gravels A with gravel B above

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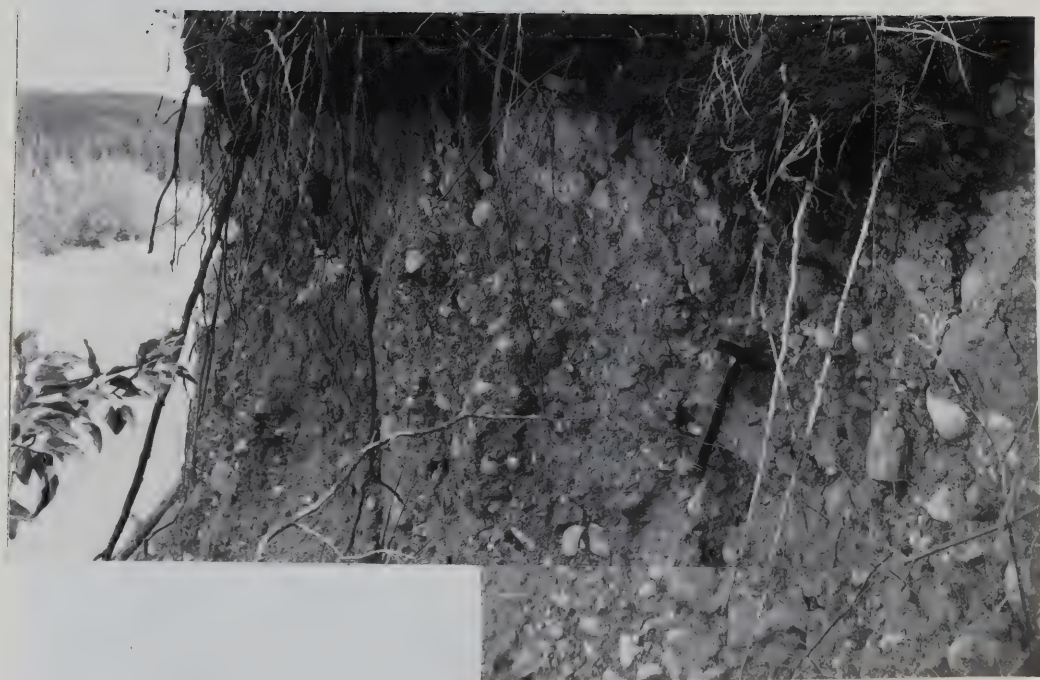


PLATE 18

Shows gravels 'A' (Fig. 28) in the lower left. Till contents include a mixture of well rounded pebbles. (Till = Till I figure 28).



PLATE 19

Section from garbage pit at site 3, near the Elbow Ranger Station. Shows medium coarse gravels poorly bedded.



PLATE 20

Shows sand lens in gravels exposed at site 3. Current flowed from left to right.

grain size distributions fall into two groups. The first group is unimodal with a median grain size between 16mm and 32mm. The second group is bimodal with peaks between 4mm to 8mm, and 32mm to 64mm. The bulk field samples referred to in Chapter 2 were taken near Elbow Ranger Station (site 3) and half a mile east of the Kinsman Camp (site 83). The results of comparing samples taken from the horizontal and the vertical in each section showed negligible differences in the total percentage contribution of material greater than 16mm, as the figures below illustrate:

Site	Horizontal	Vertical
3	57.1 %	52.9 %
83	53.3 %	55.2 %

The samples from the horizontal (Plates 21, 22, and 23) might be considered as representing distributions of material in space at one point (or one depositional phase) in time. The samples from the vertical (Plate 23) might represent the mean depositional characteristics in time, either in one phase or between several phases of deposition. In essence therefore, the above suggests that the depositional environment was consistent in time and space. The greatest thickness of gravels is approximately 100 feet, found locally between the Elbow Ranger Station and Beaver Flats. Throughout the upstream section the valley sides are benched. The fluvial material beneath all the benches is similar to that described above. In addition, the benches are cut in till and bedrock

PLATE 21

Grid overlying section on the horizontal--cleared to a depth of 9 inches. Site 3. Sampe 400. 1970.



PLATE 22

As in plate 21, showing coarser gravels. Site 83. Sampe 300. 1970.

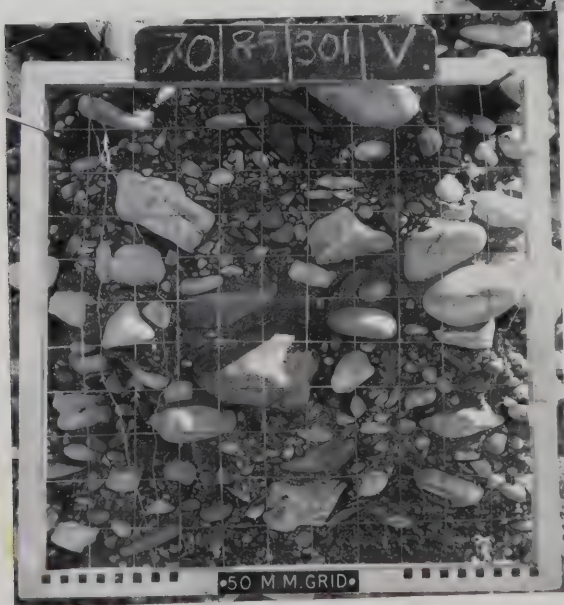
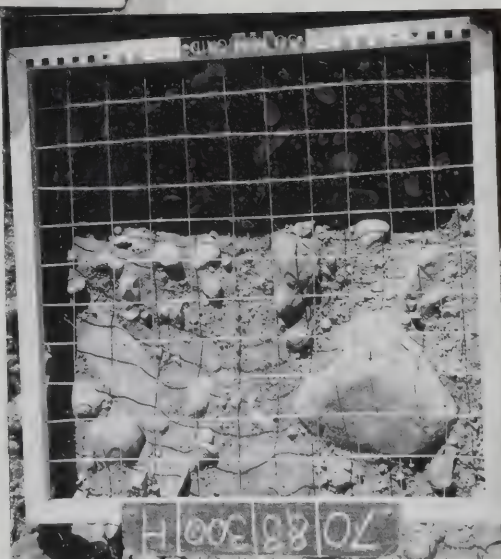


PLATE 23

Taken at the same site as plate 22, but in a vertical section. Note the apparent lack of fines (less than 8mm).

at different locations and varying elevations. The conclusion is that the gravels accumulated rapidly, with each successive retreat of the Elbow ice from constriction to constriction. As Figure 29 indicates, the greatest phase of outwash occurred when ice had retreated as far as Beaver Flats.

In a few sections a form of bedding structure is obvious. The bedding is distinguishable in terms of the matrix for pebbles greater than 8mm. The distinctiveness of the bedding is therefore in the clay, silt and sand fractions. One such case is found in Bragg Creek just below an end moraine at site 106 (Plate 24). In the higher terraces upstream of McLean Creek (Fig. 29), the bedding is less obvious, though at site 135 a more strongly bedded section was found. This contained one bed (Plates 25 and 26) which had no material less than 16mm in size. This may indicate a form of seasonal persistence of flow with seasonal high flows of considerable discharge. The changing nature of the matrix suggests extensive channel migration in a braiding system. In all, this would indicate the initial aggradation of the valley infill as an outwash plain or sandur (Plates 27 and 28). This is because valley reaches between successive constrictions seem to have individual terrace and bench sequences. The only exception is found near the Elbow Ranger Station where the highest terrace (number 12, in Fig. 29) at this point of the valley extends downstream across the Elbow Ranger Station constriction.

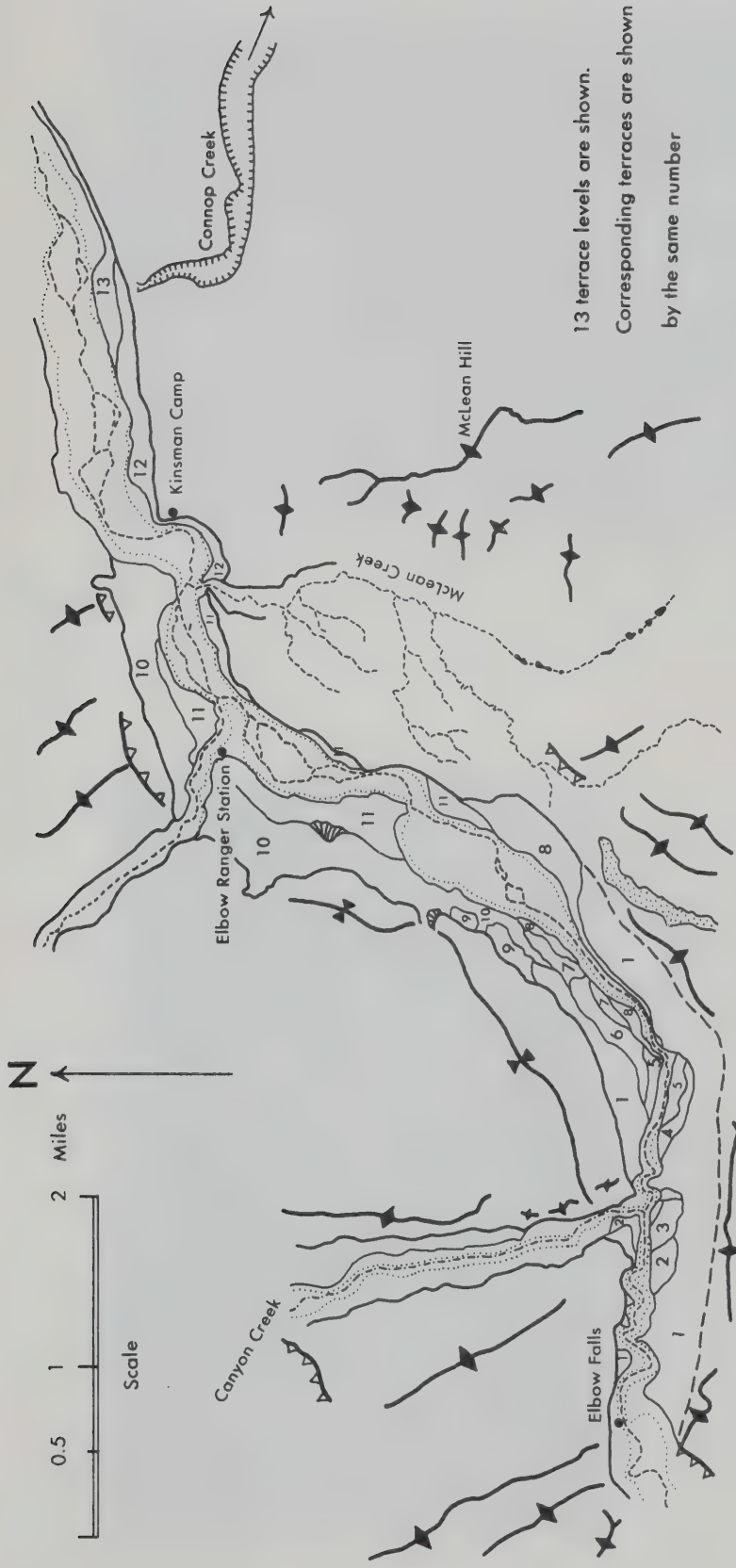


Silt and sand matrix
Cobbles and boulders.

Gravel and sand matrix.
Cobbles.

PLATE 24

Site 106. The ruler transgresses two types of matrix in the gravels. The finer matrix is associated with re-excavation or re-exposure of till for the transportation of fines.



13 terrace levels are shown.

Corresponding terraces are shown by the same number

- Prominent high relief ridges
- Linearly accordant depressions in ridges
- Glacially scoured valley side
- Boundary of fluvial sediments associated with the Elbow River
- Interpolated limit of fluvial sediments
- River—constant flow
- River—seasonal flow
- Edge of floodplain
- Depression occupied by bog
- Slumped terrace edges

Figure 29

RIVER TERRACES IN THE ELBOW VALLEY



PLATE 25

General view of section at site 135.



PLATE 26

Shows gravel bed at the base of the ruler in which there is no material less than 16mm in size.

Arrows on plate 25 locate the position of the ruler in site 135, in which this photograph was taken.



PLATE 27

View east from position 200 yards west of site 149 (west of Canyon Creek). Note extensive gravel terraces in the base of the valley.



PLATE 28

View west from site 149. Shows Prairie Mt. in the left centre, and the upstream end of the extensive terraces shown in plate 27.

Upstream of this point till is found in isolated sections below the terrace gravels. The top of the till near the Elbow Ranger Station is almost at the same level as the bedrock in the constriction at this point in the valley. This may indicate an initial phase of degradation in the glacial infill prior to accumulation of outwash. Hence, the sandur may have developed on a plain which was graded by the river between the bedrock knickpoint at the Elbow Ranger Station, and the snout of the glacier near Beaver Flats. At the point in time when this major aggradational phase terminated, the asymmetry of the Elbow River and the bedrock valley was most probably established. This is because the river became independent of the control of a bedrock valley.

Channel incision occurred subsequent to the climax of aggradation of the valley. As shown in Figure 29, the degradation was fairly continuous, as suggested by the unpaired nature of the benches. The problem of correlating benches is heightened by a relatively steep gradient in most cases upstream of the Kinsman Camp. Hence, evaluation of any notable periods of incision is not possible at this time.

The deep gorge traceable for one mile below Beaver Flats is cut through gravels and then into bedrock. When the gorge was cut is not directly determinable. If the gorge is pre-glacial, it seems improbable that the same gorge was re-occupied without considerable lateral wandering of the river. The latter would not permit the side of the gorge to extend vertically into the gravels. However,

within the gorge active rock falls are found and the Elbow Falls shows signs of retreat upstream. For example, scour marks are found in front of the falls. This suggests post-glacial formation of the gorge. The only dating factor for the change from an aggradational to a degradational fluvial environment is that Mazama ash is found on the highest terraces upstream of the Elbow Ranger Station.

Summary

At the present, upstream of Bragg Creek town site, the river appears to be adjusting to local changes in base level. Hence, between Bragg Creek and the Kinsman Camp, degradation is active as the river adjusts to the lower base level at Bragg Creek road bridge. Upstream of the Kinsman Camp, the local base levels still operate to some extent, although it is felt that a point is being reached where long term flow characteristics will determine the aggradation and degradation response of the river. An additional factor will be changes in the courses of the river. At present the river is located in mid-floodplain or erodes laterally into a bedrock valley side. Should the river course adjust to erode into the benched gravels then more active aggradation may occur. In essence therefore, a quasi-equilibrium may have been attained, with a greater tendency for degradation.

The Elbow River Downstream of Bragg Creek

In the downstream section below Bragg Creek road bridge, the major controls are the valley side material, the bedload material, and differential transportation of material. The initial establishment of the valley postdates Bragg Lake and Lake Elbow. The depth of coarse gravels (which are as coarse as upstream of Bragg Creek) is in excess of 30 feet in places above bedrock (Hollingshead, 1968). It is probable that the valley was established synchronous with the building of the outwash plains. Subsequent transport of coarse gravels downstream increased the depth of the valley by concentrating flow with a heavy bedload. In theory therefore, the influx of coarse debris caused aggradation once bedrock had been reached. The degree of control of base level at the confluence with the Bow River is difficult to establish. The Bow River has incised considerably, but Stalker (1961) states that the modern Bow River is higher than the pre-glacial Bow River, which suggests continuing degradation at the Elbow's confluence with the Bow. Evidence of initial adjustment of the Elbow River to a lower base level is found in the steep valley sides directly flanking the present floodplain. Yet, as mentioned above, 30 feet of coarse gravels have accumulated in this valley. It appears that change in the bedload material is the major factor to be considered in the evaluation of the aggradational-degradational behaviour for the immediate post-glacial period. Hence, the following

concerns the recent behaviour of the Elbow River.

The floodplain is widest near the Elbow Bridge. At present the river in this stretch and for most of its course below Bragg Creek is on the north side of the floodplain. However, sixty years ago the main stream was on the south side in this stretch, according to personal communication with the local inhabitants. Also within the same area, aerial photographs show that white spruce and lodgepole pine stands differentiate small differences in elevation of channel bars. From field observations these differences reflect increased incision of the river, as well as a tendency for migration of the less intensely braided open channel areas (Plate 29). The channel pattern is essentially an irregular meander, which during June high flow periods becomes markedly braided. The remnants of the braided channels fall in zones as mentioned above. A noticeable occurrence is the association of cross valley benches with straight, less braided channel reaches. This suggests local aggradation and degradation reaches.

In 1968, Hollingshead noticed a marked decrease in median grain size close to Twin Bridges, which continued downstream. It is unlikely that this change is related to the Glenmore Reservoir, which is now the base level of the Elbow River. The cause of the change in bedload is probably attributable to flow and selective transportation, rather than the reservoir. Since the finer bedload extends into the reservoir, the conditions causing the formation



PLATE 29

View S.W. from site 79 shows the floodplain of the Elbow River upstream of Elbow Bridge. Note the vegetation on the floodplain.

of this reach must still operate. Hence, this accumulation of finer gravels is continuing. The lower reaches of the downstream section are steeper and more irregular than might be anticipated. The local steepening of the gradient approximates the gradient at the cross valley benches mentioned earlier. A possible cause of the gradient changes may be limits of advance of debris loads attributable to phases of high flow in neo-glacial times.

Summary

It would seem that below Bragg Creek the coarse gravel reaches are being degraded as finer gravels are carried downstream, and clay and silt accumulate in the floodplain. In the lower reaches aggradation is occurring.

The behaviour of the Elbow River within the study area is changing as present flow conditions cause increasing selective transportation. As a result of this action and bedrock controls upstream of Bragg Creek, changes in quasi-equilibrium reaches may contribute to changes in strongly aggrading reaches.

CONCLUSION

This study investigates morphological and sediment characteristics, and analyses the behaviour of the present Elbow River and its basin. The major objective was to provide a basis for assimilation of the earlier, more specific studies, and to indicate useful further research.

The information upon which this study is based falls into three categories. The first concerns sediment samples which were collected and analysed for the grain size content. The results of this analysis were then used to determine the reliability of the original diagnosis of the sediment type of each sample made in the field. Principal component analysis was used to classify sediments according to grain size content. Justification for the use of principal component analysis in this context is presented in Chapter 2. The second category concerns the collection of morphological information in the field, from aerial photographs, and from topographic maps. The third category involves the collation of information, from previous studies, concerning the geologic history of the study area.

The findings of this study may be considered in four parts. The first is pre-Pleistocene geologic history, the second Pleistocene geomorphology, the third part behaviour of the Elbow River, and fourth the granulometric analysis.

The analysis of summit peak data from within the Elbow basin indicated that the topography of the foothills is closely related to geologic structure, and that the topography of the Prairies is more independent of structure. In addition, it has been shown that a sub-aerial environment existed in the study area prior to earth movements of the Laramide orogeny, and this environment persisted throughout the Tertiary era. It has proved difficult to conclude whether drainage is antecedent to geologic structure or superimposed from a mid-Tertiary peneplain in the foothills. The drainage of the Prairies, marginal to the foothills, is more closely related to peneplanation forms of a Tertiary age.

The Pleistocene geomorphology of the basin is attributed to the effects of the Wisconsin glaciation. The two ice masses which affected the study area are Cordilleran and Laurentide in origin. The extent to which each ice mass covered the area is inferred from two separate parts of the study area. The eastern part is associated with Laurentide ice deposition in the prairies, while the western area is associated with erosion and deposition in the foothills by Cordilleran ice. The dividing line between these two parts of the study area is associated with the western limit of advance of Laurentide ice, which is thought to be along a line through Sarcee Butte and Sarcee Ridge. The formation of two ice front lakes is attributed to (a) the limit of advance of Laurentide ice (Bragg Lake),

and (b) to a minor advance stage during the final retreat of this ice (Lake Elbow). In the foothills the glacial deposits are attributed to Cordilleran ice which originated within the Elbow basin, upstream of Beaver Flats. A smaller glacier is thought to have occupied Bragg Creek valley with a source area on the eastern flank of Moose Mountain Dome. The main depositional feature of the foothills in the study area is a thick infill of fluvial sediments in the Elbow River valley, upstream of Bragg Creek. These deposits are thought to be part of an outwash plain.

The present Elbow River, downstream of Bragg Creek, appears to be degrading in the coarse gravels, as finer gravels are carried downstream. In the lower reaches, above the Glenmore Reservoir, aggradation of the finer gravels occurs. Upstream of Bragg Creek selective transport of sediment, and the frequent occurrence of bedrock control, cause local quasi-equilibrium states of the longitudinal profile. As bedrock control is minimised, degradation extends upstream until a new quasi-equilibrium state is reached. This is believed to account for the behaviour of the Elbow River at the Provincial Park, near Bragg Creek.

The analysis of grain size data has shown that principal component analysis can be used to discriminate between sediment types. In addition, this statistical technique identified the obscure cases where additional geological information was required to substantiate the original sediment type allocation.

Future Research

In the author's opinion the determination of the geomorphic history of the Elbow basin depends upon more detailed examination of the surficial deposits. The systematic examination of morainic material, deposits on hillslopes in the foothills, lake sediments, and the relationship of ash deposits to terrace levels are needed. The study area, which includes part of three major topographic regions in southern Alberta, may yield valuable information concerning the pre-Wisconsin glacial events, limits of advance of Laurentide ice, and the modification of pre-glacial drainage.

A systematic investigation of the Elbow River is warranted in view of the change in sediment regime upstream. The primary features requiring investigation are sediment transport rates, hydrological characteristics, channel behaviour, and river patterns.

Principal component analysis is a useful tool in the field of environment discrimination in the spatial context. It is felt that the procedure outlined in Chapter 2 could be applied to a smaller area, in which a more controlled sample plan for the collection of sediment samples could be employed. This would permit a more reliable understanding of the statistical and spatial aspects of this analysis to be achieved.

BIBLIOGRAPHY

BIBLIOGRAPHY

- Allen P. and W. C. Krumbein, 1962, Secondary Trend Components on the Top Ashdown Pebble Bed: A Case History, Journal of Geology, Vol. 70, No. 5, pp. 507-538.
- Anderson T. W., 1958, Introduction to Multivariate Statistics, New York, John Wiley and Sons, Inc., p. 374.
- Beach H. H., 1943, Moose Mountain and Morley Map-Areas, Alberta, Geological Survey of Canada, Memoir 236, p. 74.
- Board C., 1965, Maps as Models, in Models in Geography, ed. by Chorley R. J. and P. Haggett, Chapter 16, ff. 716, London, Methuen and Co., Ltd.,
- Brown E. H., 1957, The Physique of Wales, Geographical Journal, Vol. 123, No. 2, pp. 208-230.
- Cairnes D. D., 1907, Moose Mountain District of Southern Alberta, Geological Survey of Canada, No. 968, p. 55.
- Carlson V. A., 1969, Bedrock Topography of the Drumheller Map-Area, NTS 82P, Alberta, Research Council of Alberta, Map only (1:250,000 Scale).
- , 1969A, Bedrock Topography of the Gleichen Map-Area, Alberta, Research Council of Alberta, Map No. 67-2A.
- , 1970, Bedrock Topography of the Medicine Hat Map-Area, NTS 72L, Alberta, Research Council of Alberta, Map only (1:250,000 Scale).
- Chorley R. J. and P. Haggett, 1965, Trend Surface Mapping in Geographical Research, Transactions of the Institute of British Geographers, Vol. 37, pp. 47-67.
- Crickmay C. H., 1933, The Later Stages of the Cycle of Erosion, Geological Magazine, Vol. 70, pp. 337-347.
- , 1965, An Interpretation of Erosional Discrepancy, Cypress Hills, in the Alberta Society of Petroleum Geologists, Guide Book, Part 1, Cypress Hills Plateau, pp. 66-73.

- Dawson G. M., 1885, Report on Region in the Vicinity of Bow and Belly Rivers, Northwest Territories, Geology and Natural History Survey of Canada, Report of Progress 1882-84.
- Deeprrose R. K., 1965, Elbow River Flood Report, Internal Report of the Hydrology Section, Water Resources Division, Alberta Department of Agriculture.
- Dixon W. J., 1968, Biomedical Computer Programs, Berkeley and Los Angeles, University of California Press, Class M, No. BMD01M, pp. 150-158.
- Elliot R. H., 1958, Sub-surface Correlation of the Edmonton Formation, Edmonton Geological Society Quarterly, Vol. 2, No. 2, pp. 1-8.
- Farvolden R. N., 1963, Bedrock Channels in Southern Alberta, Research Council of Alberta, Bulletin No. 12, pp. 63-75.
- Folk R. L. and W. C. Ward, 1957, Brazos River Bar: A Study in the Significance of Grain Size Parameters, Journal of Sedimentary Petrology, Vol. 27, No. 1, pp. 3-26.
- Friedman G. M., 1961, Distinction Between Dune, Beach and River Sands from Their Textural Characteristics, Journal of Sedimentary Petrology, Vol. 31, pp. 514-529.
- , 1962, On Sorting, Sorting Coefficients, and the Lognormality of the Grain Size Distribution of Sandstones, Journal of Geology, Vol. 70, No. 6, pp. 737-753.
- Geiger K. W., 1965, Bedrock Topography of Southwestern Alberta, Research Council of Alberta, Preliminary Report 65-1, p. 14.
- Gould P. R., 1967, On the Geographic Interpretation of Eigenvalues, Transactions of the Institute of British Geographers, Vol. 45, pp. 53-86.
- Greenwood B., 1969, Sediment Parameters and Environment Discrimination: An Application of Multivariate Statistics, Canadian Journal of Earth Science, Vol. 6, No. 6, pp. 1347-1358.
- Hollingshead A. B., 1967, Measurements of the Bedload Discharge of the Elbow River, Unpublished M.Sc. Thesis, Department of Civil Engineering, University of Alberta.

, 1968, Sediment Transport Measurements; Elbow River at Bragg Creek, Unpublished Report of the Research Council of Alberta, Highway and River Engineering Division.

, 1969, Sedimentation Study; Glenmore Reservoir, Unpublished Report of the Research Council of Alberta, Highway and River Engineering Division.

Hume G. S., 1928, Oil Prospects Near Bragg Creek, Alberta, Geological Survey of Canada, Summary Report 1927, Pt. B, pp. 1-20.

, 1930, The Highwood-Jumpingpound Anticline, with Notes on Turner Valley, New Black Diamond, and Priddis Valley Structures, Alberta, Geological Survey of Canada, Summary Report 1929, Pt. B, pp. 1-24.

, 1931, Overthrust Faulting and Oil Prospects of the Eastern Foothills of Alberta Between the Bow and Highwood Rivers, Economic Geology, Vol. 26, pp. 258-273.

Inman D. L., 1952, Measures for Describing the Size Distribution of Sediments, Journal of Sedimentary Petrology, Vol. 22, pp. 124-145.

Kellerhals R. and D. I. Bray, 1970, Sampling Procedure for Coarse Fluvial Sediments, A paper presented to the Hydraulic Specialty Conference, American Society of Civil Engineers, Minneapolis, pp. 1-30.

Kendall M. G., 1939, The Geographical Distribution of Crop Productivity in England, Journal of the Royal Statistical Society, Vol. 102, pp. 21-48.

King C. A. M., 1967, An Introduction to Trend Surface Analysis, Bulletin of Quantitative Data Geography, No. 12, Nottingham University, p. 39.

, 1969, Trend Surface Analysis of Central Pennine Erosion Surfaces, Transactions of the Institute of British Geographers, Vol. 47, pp. 47-61.

King L. J., 1969, Statistical Analysis in Geography, New Jersey, Prentice Hall, Inc., Chapter 7, pp. 165-193.

Krumbein W. C., 1937, Sediments and Exponential Curves, Journal of Geology, Vol. 45, pp. 577-601.

, 1938, Manual of Sedimentary Petrography, New York, Appleton-Century-Croft, Chapter 8, pp. 212-267.

, 1959, Trend Surface Analysis of Contour Type Maps with Irregular Control-Point Spacing, Journal of Geophysical Research, Vol. 64, pp. 823-834.

- Krumbein W. C. and F. A. Graybill, 1965, An Introduction to Statistical Methods in Geology, New York, McGraw-Hill, Chapter 13, pp. 327-354.
- Landim P. M. B. and L. A. Frakes, 1968, Distinction Between Tills and Other Diamictos Based on Textural Characteristics, Journal of Sedimentary Petrology, Vol. 38, No. 4, pp. 1213-1223.
- Lawley D. N. and A. E. Maxwell, 1963, Factor Analysis as a Statistical Method, London, Butterworth and Co. (Publishers) Ltd., p. 236.
- Lee P. J., 1969, The Theory and Application of Canonical Trend Surfaces, Journal of Geology, Vol. 77, No. 3, pp. 303-318.
- Link A. G., 1966, Textural Characteristics of Sediment, Sedimentology, Vol. 7, pp. 249-254.
- McCammon R. B., 1962, Efficiencies of Percentile Measurements For Describing the Mean Size and Sorting of Sedimentary Particles, Journal of Geology, Vol. 70, No. 4, pp. 453-465.
- McCrossan R. G. and R. P. Glaister, 1964, Geological History of Western Canada, Calgary, Alberta Society of Petroleum Geologists, p. 232.
- Meyboom P., 1961, The Ground Water Resources of the City of Calgary and Vicinity, Research Council of Alberta, Bulletin, No. 8, p. 72
- Middleton G. V., 1962, On Sorting, Sorting Coefficients and the Lognormality of the Grain Size Distribution of Sandstones: A Discussion, Journal of Geology, Vol. 70, No. 6, pp. 754-756.
- Morgan A. V., 1966, Lithological and Glacial Geomorphological Studies Near the Erratics Train, Calgary, Alberta, Unpublished M.Sc. Thesis, Department of Geography, University of Calgary, Alberta.
- Nichols D. A., 1931, Terminal Moraines of the Pleistocene Ice Sheets in the Jumpingpound, Wildcat Hills Area, Alberta, Transactions of the Royal Society of Canada, Series 3, Vol. 25, Section 4, p. 49.
- Ogawara M. and H. Yamazaki, 1952, Statistical Method of Estimating Isolines, Papers in Meteorology and Geophysics, Vol. 3, No. 2, pp. 77-93.

- O'Leary M., Lippert R. H. and O. T. Spitz, 1966, Fortran IV and Map Program for Computation and Plotting of Trend Surfaces for Degrees 1 Through 6, Computer Contribution No. 3, State Geological Survey, University of Kansas.
- Pannekoek A. J., 1967, Generalized Contour Maps, Summit Level Maps, and Streamline Surface Maps as Geomorphological Tools, Zeitschrift fur Geomorphologie, Vol. 11, pp. 169-182.
- Pers. Comm., Mr. A. B. Hollingshead, 1970, Research Council of Alberta, Edmonton, Alberta.
- , Mr. Murray, 1970, Springbank, Calgary, Alberta.
- , Mr. W. Poliquin, 1970, Eastern Rockies Forest Conservation Board, The John Bowlen Building, 7th Avenue, Calgary, S.W., Alberta.
- , Mr. M. Walker, 1970, Department of Geography, University of Calgary, Calgary 44, Alberta.
- , Dr. N. W. Rutter, 1970, Geological Survey of Canada, Western Division, Institute of Sedimentary and Petroleum Geology, 3303 33rd Street, N. W., Calgary, Alberta.
- , Dr. J. A. Westgate, 1970, Department of Geology, University of Alberta, Edmonton 7, Alberta.
- Russell L. S., 1932, The Cretaceous-Tertiary Transition of Alberta, Transactions of the Royal Society of Canada, Series 3, Vol. 26, Section 4, pp. 121-156.
- , 1950, The Tertiary Gravels of Saskatchewan, Transactions of the Royal Society of Canada, Series 3, Vol. 44, Section 4, pp. 51-59.
- , 1957, Tertiary Plains of Alberta and Saskatchewan, Geological Survey of Canada, Proceedings, Vol. 9, pp. 17-19.
- Sahu B. K., 1964, Depositional Mechanisms From the Size Analysis of Clastic Sediments, Journal of Sedimentary Petrology, Vol. 34, pp. 73-83.
- Shepard F. P. and R. Young, 1961, Distinguishing Between Beach and Dune Sands, Journal of Sedimentary Petrology, Vol. 31, pp. 196-214.
- Sissons J. B., 1960, Erosion Surfaces, Cyclic Slopes and Drainage Systems in Southern Scotland and Northern England, Transactions of the Institute of British Geographers, Vol. 28, pp. 23.

- Slipper S. E., 1921, Sheep River Gas and Oil Field, Alberta, Geological Survey of Canada, Memoir 122, p. 18.
- Smith D. G. W. and J. A. Westgate, 1969, Electron Probe Technique for Characterising Pyroclastic Deposits, Earth and Planetary Science Letters, Vol. 5, No. 5, pp. 313-319.
- Sparks B. W., 1964, Geomorphology, London, Longmans, Green and Co. Ltd., Chapter 15, pp. 334-362.
- Stalker A. M. 1960, Surficial Geology of the Red Deer - Stettler Map - Area, Alberta, Geological Survey of Canada, Memoir 306, p. 140.
- , Buried Valleys in Central and Southern Alberta, Geological Survey of Canada, Paper 60-32, p. 13.
- Tanner W. F., 1958, The Zig-Zag Nature of Type I and Type IV Curves, Journal of Sedimentary Petrology, Vol. 28, pp. 372-375.
- Tarrant J., 1970, Comments on the Use of Trend Surface Analysis in the Study of Erosion Surfaces, Transactions of the Institute of British Geographers, Vol. 51, pp. 221-222.
- Tharin J. C., 1960, Glacial Geology of the Calgary Area, Alberta, Unpublished Ph.D. Thesis, University of Illinois.
- Tozer E. T., 1956, Uppermost Cretaceous and Paleocene Non-Marine Molluscan Faunas of Western Canada, Geological Survey of Canada, Memoir 280, p. 125.
- Wentworth C. K., 1922, A Scale of Grade and Class Terms for Clastic Sediments, Journal of Geology, Vol. 30, pp. 377-392.
- Westgate J. A., 1965, The Geomorphology of the Cypress Hills-Milk River Canyon Area, Alberta, in the Alberta Society of Petroleum Geologists 15th Annual Field Conference, Guide Book, Part 1, Cypress Hills Plateau, pp. 74-84.
- Westgate J. A. and A. Dreimanis, 1967, Volcanic Ash Layers of Recent Age at Banff National Park, Alberta, Canada, Canadian Journal of Earth Science, Vol. 4, No. 2, pp. 155.

- Whitten E. H. T., 1963, A Surface Fitting Program Suitable for Testing Geological Models Which Involve Areal Distributed Data, Office of Naval Research, Geographical Branch, Technical Report No. 2, O.N.R. Task No. 389-135.
- Wooldridge S. W. and D. L. Linton, 1955, Structure, Surface and Drainage of Southeast England, London, George Philip and Sons Ltd., Chapters IV and V, pp. 34-59.
- Wyatt F. A., Newton J. D. and W. E. Bowser, 1960, Soil Survey of Blackfoot and Calgary Sheets, University of Alberta Bulletin, No. SS-2, Revised Edition by Peters, T. W. and W. E. Bowser, University of Alberta Bulletin, No. 39, p. 44.
- Yaremko E. K. and M. Mustapha, 1967, Evaluation of Sediment Survey Program, Glenmore Reservoir, Alberta Water Resources Division, Internal Report.

APPENDICES

APPENDIX 1

PROGRAM LISTING FOR CALCULATION AND PLOTTING OF GRAIN SIZE DATA

This program was prepared by G. C. Seagel, in December, 1970. The program calculates the percentages, cumulative percentage and an expression for the logarithm of the cumulative percentage. The latter is generated from natural logarithms to enable the plotting of the curve. The program is easily arranged so that Folk and Ward (1957) descriptive statistics may be generated.

SIEVE	=	mesh size in millemetres.
PHI	=	phi equivalent for sieves used.
NSAMP	=	identification number of each sample (in 'A' format.)
LSITE	=	site number (in 'A' format).
WT	=	weight of material retained by sieve X, and associated with sieve X + 1, as sieved finer than sieve size X + 1.

The program is presently arranged to take and compute for 19 consecutive grain size classes.

The Program:

```

        DIMENSION SIEVE(20),PHI(20),WT(20),CUMWT(20),
                    PCWT(20),CUMPC(20),XL
        1(20),XLOG(20),XNORM(20),MIN(20),MAX(20),NEWIN(20),
                    IHIST(20,101),LP
        2LT(20,101),GRP(7)
        INTEGER EYE,CUPLT(20,101)
        INTEGER BL/' '/,FD/'+'/'
        DO 1 J=1,19
        READ(5,1001) SIEVE(J),PHI(J)
1001  FORMAT(F7.3,F4.1)
        1  CONTINUE
        99  READ(5,1002) NSAMP,LSITE
1002  FORMAT(A4,A4)
        READ(5,1003) (WT(J),J=1,19)
1003  FORMAT(10F8.2/9F8.2)
        DO 100 I=1,19
        DO 101 J=1,101
        IHIST(I,J)=BL
        CUPLT(I,J)=BL
101  LPLT(I,J)=BL
100  CONTINUE
C      CALCULATE CUMULATIVE PERCENT
        TOTWT=0.0
        DO 10 J=1,19
        TOTWT=TOTWT+WT(J)
10  CUMWT(J)=TOTWT
        CUM2=0.0

```



```

DO 11 J=1,19

CUM=(WT(J)/TOTWT)*100.0

PCWT(J)=CUM

CUM2=CUM2+CUM

11  CUMPC(J)=CUM2

C    CALCULATE GROUP PERCENTS FOR SEVEN GROUPS

DO 15 I=1,7

15  GRP(I)=0.0

GRP(1)=PCWT(1)

GRP(2)=PCWT(2)+PCWT(3)+PCWT(4)+PCWT(5)

GRP(3)=PCWT(6)+PCWT(7)+PCWT(8)+PCWT(9)

GRP(4)=PCWT(10)+PCWT(11)+PCWT(12)+PCWT(13)

GRP(5)=PCWT(14)+PCWT(15)

GRP(6)=PCWT(16)+PCWT(17)

GRP(7)=PCWT(18)+PCWT(19)

C    CALCULATE LOG. CUMULATIVE PERCENT

DO 20 J=1,19

XL(J)=CUMPC(J)*10000.0

XLOG(J)=ALOG(XL(J))

XNORM(J)=(XLOG(J)*10.0)-130.0)*10.0

IF(XNORM(J).LT.0.0)XNORM(J)=0.0

LOAD=IFIX(XNORM(J))

REG=XNORM(J)-LOAD

IF(REG-0.5)22,23,23

22  MIN(J)=LOAD

GO TO 20

23  MIN(J)=LOAD+1

```



```

20  CONTINUE

C    LIST SIEVE SIZE, PHI, PERCENT WT, CUMULATIVE PERCENT
C    WT, LOG. OF CUMULATIVE PERCENT, AND SEVEN GROUP
      PERCENTS.

      WRITE(6,2002) NSAMP, LSITE

2002  FORMAT('1'////,40X,'GRAIN SIZE ANALYSIS'//10X,'
          SAMPLE NUMBER = ',A
14,10X,'SITE NUMBER = ',A4//10X,'SIEVE SIZE IN M
          M.',5X,'PHI VALUE',
210X,'PERCENT WT',13X,'CUMULATIVE PERCENT',5X,'L
          OG. OF CUMULATIVE P
3ERCENT')

      DO 30 J=1,19

      WRITE(6,2003) SIEVE(J),PHI(J),PCWT(J),CUMPC(J),
          XNORM(J)

2003  FORMAT(/10X,F7.3,15X,F4.1,15X,F8.4,15X,F8.4,
          15X,F8.4)

30  CONTINUE

      WRITE(6,2050) (GRP(I),I=1,7)

2050  FORMAT('1'////10X,'GROUPED DATA BY PERCENT WT.
          , AFTER WENTWORTH'//
1/10X,'SILT-CLAY',11X,F8.4//10X,'FINE SAND',11X,
          F8.4//10X,'MEDIUM S
2AND',9X,F8.4//10X,'COARSE SAND',9X,F8.4//10X,'G
          RAVEL',14X,F8.4//10
3X,'COBBLES',13X,F8.4//10X,'BOULDERS',12X,F8.4)

C    PLOT HISTOGRAM

C    CONVERT TO WHOLE NUMBERS

      DO 40 J=1,19

```



```

      KOLD=IFIX (PCWT (J) )
      REK=PCWT (J) -KOLD
      IF (REK=0.5) 41,42,42
41    MAX (J)=KOLD
      GO TO 40
42    MAX (J)=KOLD+1
40    CONTINUE
      DO 51 J=1,19
      K=MAX (J)
51    IHIST (J,K)=FD
      WRITE (6,2010) NSAMP,LSITE
2010  FORMAT ('1'///20X,'HISTOGRAM OF PERCENT WT. I
           N EACH GRAIN SIZE CLAS
           1S'//15X,'SAMPLE NUMBER = ',A4,10X,'SITE NUMBER =
           ',A4///56X,'PERCE
           2NT WEIGHT')
      WRITE (6,2011)
2011  FORMAT (//17X,'0',8X,'10',8X,'20',8X,'30',8X,
           '40',8X,'50',8X,'60',8
           1X,'70'8X,'80',8X,'90',7X,'100'/17X,' ',10(9X,' '))
      DO 54 I=1,13
      WRITE (6,2012) SIEVE (I) , (IHIST (I,K) ,K=1,101)
2012  FORMAT (14X,' '/4X,F7.3,2X,'- ',3X,101A1)
      54  CONTINUE
      DO 59 I=14,19
      WRITE (6,2912) SIEVE (I) , (IHIST (I,K) ,K=1,101)
2912  FORMAT (14X,' '/14X,' '/4X,F7.3,2X,'- ',3X,101A1)
      59  CONTINUE

```



```

C      PLOT CUMULATIVE PERCENT CURVE.
C      CONVERT TO WHOLE NUMBERS.

      DO 60 J=1,19

      HOLD=IFIX (CUMPC (J) )

      RES=CUMPC (J) -HOLD

      IF (RES-0.5) 61,62,62

61     NEWIN (J)=HOLD

      GO TO 60

62     NEWIN (J)+HOLD+1

60     CONTINUE

      DO 65 J=1,19

      K=NEWIN (J)

65     CUPLT (J,K)=FD

      WRITE (6,2020) NSAMP,LSITE

2020    FORMAT ('1'///20X,'PLOT OF CUMULATIVE PERCENT CURVE'
              //15X,'SAMPLE N
              LUMBER = ',A4,10X,'SITE NUMBER = ',A4///56X,'CUMULAT
              IVE PERCENT WEI
              2GHT' )

      WRITE (6,2011)

      DO 68 I=1,13

      WRITE (6,2021) SIEVE (I) ,(CUPLT (I,K) ,K=1,101)

2021    FORMAT (14X,' '/4X,F7.3,2X,'- ',3X,101A1)

68     CONTINUE

      DO 69 I=14,19

      WRITE (6,2921) SIEVE (I) ,CUPLT (I,K) ,K=1,101)

2921    FORMAT (14X,' '/14X,' '/4X,F7.3,2X,'- ',3X,101A1)

```



```

69  CONTINUE

C    PLOT LOG. CUMULATIVE PERCENT CURVE.

      DO 71 J=1,19

        K=MIN(J)

71    LPLT(J,K)=FD

        WRITE(6,2031) NSAMP,LSITE

2031  FORMAT('1'///20X,'LOG. PLOT OF CUMULATIVE PERCENT
           T CURVE'//15X,'SAM
           1PLE NUMBER = ',A4,10X,'SITE NUMBER = ',A4///56X,
           'LOG. SCALE CUMULA
           2TIVE PERCENT')

        WRITE(6,2032)

2032  FORMAT(//17X,'0',78X,'100',11X,'LOG. VALUE'/17X,
           ' ',80X,' ')

      DO 78 I=1,13

        WRITE(6,2033) SIEVE(I),(LPLT(I,K),K=1,82),XNORM(I)

2033  FORMAT(14X,' '/4X,F7.3,2X,'- ',3X,82A1,10X,F8.4)

78    CONTINUE

      DO 79 I=14,19

        WRITE(6,2933) SIEVE(I),(LPLT(I,K),K=1,82), XNORM(I)

2933  FORMAT(14X,' '/14X,' '/4X,F7.3,2X,'- ',3X,82A1,10X,
           F8.4)

79    CONTINUE

C    PUNCHED OUTPUT

      WRITE(7,3001) NSAMP, (GRP(I),I=1,7)

3001  FORMAT(A4,7F8.4)

      WRITE(7,3002) NSAMP,(PCWT(J),J=1,19)

```



```
3002  FORMAT(A4,9F8.4/10F8.4)
      WRITE(7,3002) NSAMP,(CUMPC(J),J=1,19)
C      CHECK FOR ANOTHER SAMPLE TO BE PROCESSED.
      READ(5,1005) EYE
1005  FORMAT(I1)
      IF(EYE.GT.0)GO TO 99
      STOP
      END
```


APPENDIX 2

PROGRAM LISTING FOR RANK ORDERING OF GROUPED DATA BY THE FIRST VARIABLE

This program was prepared by G. C. Seagel, in December, 1970. The program was prepared specifically for use with granulometric data. The format statements are easily changed to accommodate a greater range of data.

N is the number of vectors of observations.

WT is the vector of observations of length J (in this case $J = 8$).

S is dimensioned equal to J.

SWT is dimensioned equal to I equal to N.

The program:

```
DIMENSION WT(300,8),S(8),SWT(300)

WRITE(6,200)

200  FORMAT('1'///46X,'RANK ORDER OF GROUPED DATA &
        PERCENT WEIGHT'//)

READ(5,100) N

101  FORMAT(I3)

      READ(5,101) (WT(I,J),J=1,8)

101  FORMAT(A4,7F8.4)

1    CONTINUE

M=N-1
```



```
3  DO 12 I=1,M
    IF (WT(I+1,2).GE.WT(I,2))GO TO 12
    DO 13 J=1,8
    S(J)=WT(I+1,J)
    WT(I+1,J)=WT(I,J)
13  WT(I,J)=S(J)
12  CONTINUE
    M=M-1
    IF (M.GE.1)GO TO 3
    DO 40 I=1,N
    GQ=WT(I,2)/100.0
40  SWT(I)=(GQ**2)*100.0
    DO 20 I=1,N
    WRITE(6,201) SWT(I),(WT(I,J),J=1,8)
201 FORMAT(/10X,F8.4,5X,A4,7(5X,F8.4))
20  CONTINUE
    STOP
    END
```


APPENDIX 3

RANK ORDER MATRIX OF GRAIN SIZE PERCENTAGES

Sediment Type	Grain Size Classes Grouped into the Wentworth Grain Size Scale					
	0.063	0.250 0.063	1.000 0.250	4.000 1.000	16.00 4.00	64.00 mm 16.00 mm
FS	1.07	8.77	68.26	18.77	3.14	0.0
I	1.22	65.14	33.03	0.62	0.0	0.0
FS	1.53	61.33	37.04	0.10	0.0	0.0
FS	2.35	21.45	75.07	1.13	0.0	0.0
FS	2.42	60.50	36.88	0.21	0.0	0.0
A	2.51	13.70	53.48	25.54	4.77	0.0
I	2.74	58.46	27.16	7.13	4.51	0.0
FS	4.18	78.43	16.74	0.65	0.0	0.0
FS	5.00	56.58	38.40	0.02	0.0	0.0
FS	6.05	80.93	12.99	0.04	0.0	0.0
FS	7.01	79.39	13.45	0.15	0.0	0.0
L	9.00	87.82	3.18	0.0	0.0	0.0
FS	9.49	88.02	2.43	0.06	0.0	0.0
FS	20.04	63.53	16.27	0.17	0.0	0.0
CT	21.93	15.27	17.18	37.56	8.06	0.0
FS	23.14	21.43	32.90	22.52	0.0	0.0
L	25.67	69.95	4.30	0.09	0.0	0.0
L	28.31	69.24	2.34	0.11	0.0	0.0
L	28.39	48.68	22.93	0.0	0.0	0.0

FS	33.05	60.71	5.46	0.78	0.0	0.0
L	33.72	65.56	0.49	0.22	0.0	0.0
FS	33.72	55.41	8.47	1.63	0.77	0.0
LT	36.89	53.53	8.70	0.88	0.0	0.0
CT	37.68	17.36	9.46	11.19	20.54	3.77
A	38.37	24.43	19.11	12.13	5.96	0.0
FS	38.84	23.16	11.19	9.55	17.27	0.0
L	39.69	22.96	29.06	7.73	0.55	0.0
CT	40.64	22.29	11.15	15.20	10.71	0.0
L	41.01	57.71	1.25	0.03	0.0	0.0
CT	41.58	18.26	9.10	10.67	20.40	0.0
L	42.00	37.06	16.36	4.58	0.0	0.0
CT	42.09	11.82	8.38	16.41	21.31	0.0
L	42.88	54.87	2.23	0.02	0.0	0.0
CT	44.17	19.00	11.50	11.16	14.17	0.0
CT	44.98	15.11	8.62	11.31	19.99	0.0
CT	48.12	17.66	8.33	10.22	15.68	0.0
LT	48.19	41.11	1.50	0.83	8.37	0.0
CT	49.11	16.57	8.13	9.84	11.75	4.61
LT	49.48	41.47	7.78	1.26	0.0	0.0
CT	50.54	13.54	6.27	17.23	12.42	0.0
CT	51.26	13.19	10.45	12.31	12.80	0.0
LT	51.51	22.64	15.51	10.01	0.33	0.0
CT	52.13	20.23	14.49	12.02	1.14	0.0
CT	52.53	7.37	7.91	16.13	16.10	0.0
CT	52.72	21.69	11.10	10.29	4.19	0.0
CT	54.08	12.69	6.42	12.33	14.47	0.0

CT	54.10	15.00	6.05	9.80	15.05	0.0
L	54.34	44.51	1.07	0.08	0.0	0.0
CT	54.61	16.12	7.26	8.65	13.36	0.0
FS	55.77	43.39	0.84	0.0	0.0	0.0
CT	57.06	18.39	5.66	5.91	12.99	0.0
CT	57.11	17.52	8.11	9.57	7.70	0.0
L	58.82	40.13	0.15	0.90	0.0	0.0
L	58.90	33.51	2.35	2.50	2.75	0.0
CT	59.33	17.40	7.07	6.53	9.69	0.0
CT	59.56	17.75	6.49	9.63	6.56	0.0
CT	59.74	15.26	7.21	8.55	9.24	0.0
CT	61.58	16.57	7.43	6.02	8.41	0.0
CT	62.41	16.98	6.34	7.55	6.72	0.0
LT	62.44	16.13	4.85	3.08	13.51	0.0
LT	62.94	17.74	6.07	3.54	9.71	0.0
L	63.36	35.00	1.19	0.12	0.33	0.0
L	64.41	32.93	2.65	0.02	0.0	0.0
CT	64.92	17.48	4.66	2.65	10.29	0.0
LT	65.24	16.96	5.63	4.12	8.06	0.0
L	65.74	33.26	0.97	0.03	0.0	0.0
CT	65.82	13.73	7.75	9.31	3.38	0.0
CT	65.83	18.86	7.23	5.21	2.86	0.0
CT	66.53	16.73	6.28	6.17	4.30	0.0
CT	66.68	12.56	6.42	7.32	7.01	0.0
CT	66.88	15.32	6.03	7.26	4.51	0.0
LT	67.12	19.70	5.30	4.89	2.98	0.0
LT	67.29	13.90	4.00	2.38	12.42	0.0

LT	67.55	19.49	5.18	3.10	4.68	0.0
L	67.87	32.00	0.13	0.0	0.0	0.0
CT	67.97	14.14	7.86	7.31	2.73	0.0
L	68.13	19.15	5.45	5.81	1.46	0.0
L	68.47	26.68	4.33	0.53	0.0	0.0
L	68.50	28.81	2.22	0.47	0.0	0.0
L	68.93	27.21	3.79	0.07	0.0	0.0
L	69.50	24.78	5.24	0.48	0.0	0.0
LT	70.91	14.65	3.50	2.64	8.31	0.0
LT	71.54	14.60	3.71	2.48	7.67	0.0
CT	71.74	13.53	6.37	6.35	2.01	0.0
LT	71.88	26.30	1.59	0.23	0.0	0.0
CT	72.46	13.97	5.26	5.73	2.58	0.0
LT	72.84	21.75	2.74	1.18	1.50	0.0
L	72.89	19.70	4.14	3.28	0.0	0.0
L	73.36	25.94	0.67	0.02	0.0	0.0
LT	73.44	18.51	4.52	2.23	1.30	0.0
CT	74.25	8.81	3.76	4.92	8.27	0.0
L	74.26	23.63	2.01	0.11	0.0	0.0
L	74.76	24.17	0.99	0.08	0.0	0.0
LT	74.89	17.91	4.14	2.59	0.47	0.0
LT	75.35	18.97	3.67	1.13	0.88	0.0
LT	75.70	12.89	2.12	2.28	7.01	0.0
LT	76.65	6.03	1.52	4.31	11.49	0.0
LT	76.75	11.03	4.75	2.98	4.48	0.0
LT	76.95	17.92	1.88	1.00	2.25	0.0
L	76.97	14.19	0.96	1.43	6.45	0.0

LT	77.09	15.41	2.38	2.33	2.80	0.0
LT	77.25	16.48	2.41	1.90	1.96	0.0
LT	77.35	17.47	3.18	1.15	0.85	0.0
LT	77.62	14.71	3.00	1.11	3.56	0.0
L	77.90	21.96	0.14	0.0	0.0	0.0
LT	77.93	16.19	1.33	2.36	2.19	0.0
LT	78.50	13.11	3.26	2.07	3.06	0.0
L	78.55	21.37	0.08	0.0	0.0	0.0
LT	78.99	14.66	2.68	1.02	2.68	0.0
LT	79.44	13.39	2.67	2.14	2.35	0.0
L	79.86	17.90	2.24	0.0	0.0	0.0
L	81.59	9.19	4.18	4.18	0.87	0.0
L	81.93	14.24	3.59	0.24	0.0	0.0
LT	82.79	13.81	1.92	0.69	0.79	0.0
L	82.80	16.65	0.55	0.0	0.0	0.0
LT	82.81	7.08	2.08	1.33	6.71	0.0
LT	83.28	11.37	2.72	1.45	1.19	0.0
LT	83.67	10.94	2.74	0.94	1.72	0.0
LT	83.87	11.58	2.37	1.52	0.67	0.0
L	83.88	15.99	0.13	0.0	0.0	0.0
L	84.80	12.98	1.36	0.86	0.0	0.0
CT	85.08	10.39	3.14	0.55	0.84	0.0
L	85.84	5.93	2.07	3.25	2.91	0.0
L	86.12	13.84	0.04	0.0	0.0	0.0
L	86.59	7.87	0.62	0.71	4.21	0.0
L	87.56	12.36	0.08	0.0	0.0	0.0
CT	88.29	6.89	2.11	2.62	0.45	0.0

L	88.47	9.08	2.19	0.26	0.0	0.0
L	88.72	8.20	2.85	0.23	0.0	0.0
CT	89.21	5.50	2.46	1.69	1.14	0.0
CT	89.28	8.55	1.37	0.49	0.31	0.0
L	89.54	10.13	0.30	0.03	0.0	0.0
L	90.56	7.66	1.04	0.26	0.48	0.0
L	92.30	3.17	0.59	0.55	3.39	0.0
L	92.40	3.76	1.36	1.95	0.53	0.0
L	92.72	4.93	1.22	1.14	0.0	0.0
L	02.99	5.62	1.19	0.20	0.0	0.0
L	93.09	6.89	0.02	0.0	0.0	0.0
L	93.54	4.26	1.70	0.27	0.23	0.0
LT	93.71	4.73	0.68	0.88	0.0	0.0
L	94.82	3.19	0.62	0.82	0.55	0.0
LT	94.91	4.95	0.06	0.08	0.0	0.0
L	94.99	4.99	0.13	0.0	0.0	0.0
L	95.11	4.86	0.02	0.0	0.0	0.0
LT	95.56	2.55	0.72	1.18	0.0	0.0
L	95.72	3.19	0.68	0.42	0.0	0.0
LT	95.84	3.37	0.67	0.12	0.0	0.0
L	95.85	3.61	0.49	0.05	0.0	0.0
L	96.04	2.67	0.51	0.78	0.0	0.0
L	97.23	1.13	0.49	0.92	0.23	0.0
LT	97.31	2.23	0.30	0.17	0.0	0.0
LT	97.32	2.10	0.47	0.12	0.0	0.0
L	97.46	0.55	0.15	0.60	1.25	0.0
L	97.52	2.48	0.0	0.0	0.0	0.0

L	97.94	1.48	0.34	0.23	0.0	0.0
L	98.03	1.63	0.24	0.10	0.0	0.0
LT	98.14	1.65	0.19	0.02	0.0	0.0
L	98.14	1.69	0.14	0.03	0.0	0.0
L	98.38	1.51	0.11	0.0	0.0	0.0
L	98.53	1.22	0.13	0.13	0.0	0.0
L	98.73	0.72	0.13	0.42	0.0	0.0
L	98.76	1.09	0.15	0.0	0.0	0.0
L	98.80	0.85	0.15	0.20	0.0	0.0
L	98.80	1.07	0.13	0.0	0.0	0.0
L	98.83	0.88	0.20	0.10	0.0	0.0
L	98.87	0.64	0.15	0.33	0.0	0.0
L	98.90	0.84	0.20	0.06	0.0	0.0
L	99.01	0.64	0.17	0.17	0.0	0.0
L	99.09	0.81	0.11	0.0	0.0	0.0
L	99.12	0.71	0.14	0.04	0.0	0.0
L	99.13	0.83	0.05	0.0	0.0	0.0
L	99.15	0.69	0.16	0.0	0.0	0.0
L	99.25	0.40	0.10	0.02	0.24	0.0
L	99.25	0.42	0.07	0.0	0.25	0.0
L	99.30	0.57	0.07	0.05	0.0	0.0
L	99.35	0.58	0.07	0.0	0.0	0.0
L	99.36	0.57	0.07	0.0	0.0	0.0
L	99.40	0.60	0.0	0.0	0.0	0.0
L	99.47	0.41	0.09	0.02	0.0	0.0
L	99.51	0.20	0.16	0.12	0.0	0.0
L	99.52	0.46	0.03	0.0	0.0	0.0

L	99.54	0.33	0.10	0.03	0.0	0.0
L	99.54	0.42	0.04	0.0	0.0	0.0
L	99.56	0.44	0.0	0.0	0.0	0.0
L	99.58	0.35	0.06	0.0	0.0	0.0
L	99.64	0.36	0.0	0.0	0.0	0.0
L	99.64	0.29	0.06	0.0	0.0	0.0
L	99.86	0.14	0.0	0.0	0.0	0.0
L	99.86	0.14	0.0	0.0	0.0	0.0
L	99.88	0.12	0.0	0.0	0.0	0.0
L	99.88	0.12	0.0	0.0	0.0	0.0
L	99.89	0.11	0.0	0.0	0.0	0.0
L	99.91	0.09	0.0	0.0	0.0	0.0
L	99.91	0.09	0.0	0.0	0.0	0.0

The symbols in the column headed 'sediment type' indicate the following sediment types:

L	Lacustrine sediments
LT	Laurentide till
CT	Cordilleran till
A	Ash samples
FS	Fluvial sands
I	Ice wedge samples

APPENDIX 4

PRINCIPAL COMPONENT ANALYSIS

The data consisted of ratio numbers or percentages. Tanner (1958) points out that cumulative percentage grain size curves, which often "zig-zag", are only approximations of Gaussian curves, and that the irregularities point to forms of independence of different classes or groups of classes of grain sizes. In addition, each curve is independent, although it is known that certain curves will show distinct similarities due to common genesis. In this study the unknowns were the interrelationships between grain size classes, whilst the objective was to test for (pre-determined) groups of curves. In this case no hypothesis concerning the number of components or combinations of classes characteristic of each group was known. Since the form of the data suited principal component analysis this technique was used.

The account of principal component analysis is taken from King, L. J., 1969.

The solution to principal component analysis is essentially based on a geometric manipulation applied to matrix algebra. The object is to produce a new set of variables y_i , which are uncorrelated one with another, from an original set of variables x_i , which may well have been highly correlated. The solution involves an orthogonal

transformation of x_i to produce y_i , such that the total variance associated with x_i is preserved in the components of y_i . The geometry basically proves that the matrix $[U]$ and its transpose $[U]^T$ when multiplied, equal the identity matrix, such that $[x] = [U] \cdot [y]$, and hence $[y] = [U]^T \cdot [x]$. Lawley and Maxwell (1963), and Anderson (1958) show that this property of an orthogonal matrix may be manipulated to give a matrix containing the variance and covariance terms for the y 's in the expression

$$[U]^T \cdot \Sigma \cdot [U]$$

where Σ is the variance-covariance matrix. Since the y 's are assumed uncorrelated the off-diagonal elements of the multiplies expression are the covariance elements, and equal to zero. Hence, the diagonal will contain the variance of the y 's which are usually referred to as λ 's. For example in the three variable case

$$[U]^T \cdot \Sigma \cdot [U] = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} = [\Lambda]$$

It can be proven that $[U]^T \cdot \Sigma = [\Lambda] \cdot [U]^T$ in which case the general form of the matrix may be referred to instead of the geometric form. Since the variances on the diagonal are assumed to be unity in the transposed matrices, the solution to the above expression in terms of the variance (σ) and the λ 's is

$$\begin{vmatrix} \sigma_{11}-\lambda & \sigma_{21} & \sigma_{31} \\ \sigma_{12} & \sigma_{22}-\lambda & \sigma_{32} \\ \sigma_{13} & \sigma_{23} & \sigma_{33}-\lambda \end{vmatrix} = 0 = |\Sigma - \lambda I|$$

where I is the identity matrix, and $|\Sigma - \lambda I| = 0$ is the characteristic equation of the matrix. The solution of the equation is a polynomial expression of an order equal to the number of variables (or components of the diagonal). The λ 's are therefore the latent roots or eigenvalues, which are obtained from the coefficients of the polynomial terms in the characteristic equation. Since the eigenvalues in effect represent the amount of variance explained by each component, the rank ordering of the eigenvalues in the eigenvector will produce a canonical component listing. By substituting the eigenvector into the expression for y , the y values or loadings may be computed.

In the case of nonstandardized data each y value has to be scaled by the corresponding square root of the eigenvalue. In this case the solution for y becomes

$$[y'] = [\Lambda]^{-\frac{1}{2}} \cdot [y]$$

for an expression in terms of the variance-covariance matrix. By matrix manipulation and adoption of the convention of Lawley and Maxwell (1963) of $[W] = [U] \cdot [\Lambda]^{\frac{1}{2}}$, then it can be shown that the characteristic equation becomes

$$|R - \lambda I| = 0$$

where R is the matrix of correlations, which relates to the model

$$[Z] = [W] \cdot [y']$$

where $[Z]$ is the vector of standardized original variables.

The latter is most widely used because of the computational efficiency. It has the disadvantage of not having any means by which the significance level of the results can be readily tested.

APPENDIX 5

MATRIX OF FACTOR LOADINGS GENERATED FROM PRINCIPAL COMPONENT ANALYSIS

Component Type I.D.	Component Type I.D.	Component Type I.D.	Component Type I.D.	Component Type I.D.
₁	₂	₃	₄	
12.73 A 131	5.89 FS 180	7.73 FS 170	3.80 FS 1	
12.03 FS 171	5.81 FS 1	7.12 FS 171	3.49 FS 97	
11.06 CT 139	5.79 FS 66	5.45 FS 131	3.27 FS 77	
8.47 FS 162	5.78 I 77	2.84 FS 1	2.97 FS 5	
6.57 FS 170	5.74 FS 4	2.75 FS 155	2.56 FS 164	
5.22 CT 9	5.74 FS 5	2.64 FS 97	2.51 CT 9	
4.68 CT 141	5.69 FS 48	2.63 FS 5	2.24 CT 151	
4.67 CT 142	5.68 FS 97	2.22 FS 77	2.01 CT 133	
4.60 A 190	5.52 FS 69	1.78 FS 162	1.99 FS 66	
4.52 CT 156	4.75 FS 87	1.48 FS 164	1.96 CT 146	
4.37 L 155	4.47 FS 165	1.01 L 94	1.83 CT 161	
4.18 I 39	4.33 FS 187	1.01 L 116	1.81 FS 135	

4.13	CT	146	4.23	FS	84	1.01	L	114	1.68	I	39
3.95	CT	133	4.11	L	164	1.01	L	73	1.63	LT	23
3.88	CT	124	4.05	FS	170	1.01	L	88	1.62	LT	91
3.86	CT	151	3.86	FS	179	1.01	L	191	1.62	LT	57
3.83	CT	159	3.71	I	39	1.00	L	192	1.61	FS	69
3.66	FS	135	3.68	FS	33	1.00	L	117	1.43	FS	180
3.51	CT	120	3.53	FS	70	1.00	L	110	1.29	CT	160
3.45	CT	147	3.43	FS	36	0.99	L	11	1.24	CT	143
3.22	CT	161	3.27	FS	127	0.99	L	64	1.23	CT	142
2.91	CT	145	2.50	FS	181	0.99	L	51	1.12	CT	147
2.87	CT	119	2.45	LT	24	0.99	L	65	1.04	CT	159
2.81	CT	175	2.43	FS	98	0.99	L	118	0.97	LT	26
2.78	LT	37	1.97	L	188	0.99	L	46	0.95	FS	87
2.59	CT	150	1.95	L	185	0.99	L	115	0.91	CT	175
2.53	FS	5	1.75	LT	30	0.99	L	45	0.89	FS	170
2.48	CT	167	1.70	L	8	0.99	L	86	0.84	CT	145
2.41	FS	1	1.64	L	16	0.98	L	84	0.83	LT	89
2.34	I	77	1.55	L	122	0.98	L	169	0.72	LT	103

2.22	CT	148	1.49	L	79	0.98	L	182	0.70	CT	150
2.20	FS	97	1.24	L	49	0.98	L	68	0.68	CT	156
2.19	CT	152	1.20	L	29	0.97	L	113	0.62	LT	59
1.96	CT	189	1.15	L	178	0.97	L	134	0.56	L	124
1.82	L	188	1.13	L	177	0.97	L	105	-----		
1.70	CT	144	1.05	L	166	0.96	L	71	Investigation		
1.63	CT	149	1.01	LT	17	0.96	L	85	discontinued		
1.52	CT	143	0.96	L	32	0.96	L	52			
1.52	CT	140	0.86	L	154	0.96	L	157			
1.50	CT	121	0.82	L	31	0.96	L	136			
1.44	CT	193	0.72	L	155	0.96	L	63			
1.41	FS	180	0.64	L	95	0.94	I	39			
1.29	CT	128	0.58	L	80	0.93	LT	18			
1.09	CT	132	0.51	LT	20	0.93	L	53			
0.99	FS	69	0.43	L	7	0.93	L	10			
0.93	FS	66	0.38	LT	38	0.93	L	72			
0.93	CT	3	0.21	LT	35	0.93	L	58			
0.91	FS	87	0.21	L	153	0.92	L	44			

0.83	CT	123	0.21	LT	47	0.92	L	186
0.82	LT	90	0.20	FS	93	0.91	L	62
0.76	LT	15	0.17	L	173	0.91	L	56
0.76	FS	164	0.15	LT	101	0.90	L	82
0.74	LT	23	0.15	LT	28	0.90	L	67
0.70	CT	194	0.14	L	163	0.88	LT	100
0.63	CT	130	0.04	LT	37	0.86	L	184
0.62	CT	176	0.02	LT	75	0.85	LT	43
0.43	LT	22	-----			0.84	L	138
0.37	FS	48	Investigation			0.81	L	50
0.34	CT	160	discontinued			0.80	L	55
0.34	FS	70				0.78	LT	78
0.33	LT	91				0.77	L	174
0.29	LT	57				0.77	L	54
0.28	FS	36				0.77	LT	12
0.24	FS	4				0.77	L	111
0.20	LT	75				0.72	L	125
0.15	FS	179				0.72	L	42

0.07	LT	27	0.71	L	112
0.01	FS	165	0.70	CT	2
0.00	LT	26	0.66	L	96
-0.03	LT	24	0.66	L	104
-0.08	LT	30	0.65	LT	40
-0.12	L	158	0.64	L	172
-0.13	LT	92	0.60	CT	129
-0.17	L	178	0.60	L	83
-0.26	FS	93	0.58	LT	61
-0.27	FS	187	0.55	L	173
-0.38	LT	103	0.53	CT	137
-0.42	LT	35	0.50	LT	102
-0.51	LT	28	0.48	CT	120
-0.52	FS	34	0.47	A	190
-0.53	L	183	0.42	L	74
-0.55	FS	127	0.42	L	158
-0.57	L	60	0.42	L	188
-0.62	L	13	0.35	L	59

-0.64	FS	33	0.34	LT	109
-0.67	LT	21	0.31	LT	107
-0.73	L	99	0.30	L	41
-0.74	L	76	0.25	LT	108
-0.76	LT	89	0.22	CT	193
-0.80	LT	106	0.19	L	153
-0.80	L	166	0.18	L	166
-0.80	L	14	0.18	L	7
-0.81	LT	20	0.17	L	183
-0.82	L	177	0.17	LT	19
-0.87	LT	38	0.16	L	126
-0.92	LT	47	0.16	L	49
-0.94	LT	25	0.10	FS	87
-0.94	FS	181	0.07	LT	37
-0.97	LT	101	0.07	CT	3
-0.97	LT	107	0.04	LT	38
-0.99	L	137	0.03	LT	35
-0.99	L	185	0.02	LT	47

-1.04	FS	98	0.01	L	177
-1.04	LT	2	-----		
-1.04	L	49	Investigation		
-1.05	L	16	discontinued		
-1.05	L	29			
-1.07	L	8			
-1.08	L	108			
-1.09	L	109			
-1.20	L	129			
-1.22	L	172			
-1.22	L	122			
-1.23	L	6			
-1.23	LT	17			
-1.28	L	31			
-1.28	L	19			
-1.30	L	173			
-1.36	L	126			
-1.36	L	79			

-1.38	L	154
-1.41	L	32
-1.43	L	7
-1.43	L	125
-1.47	L	59
-1.49	L	174
-1.52	L	42
-1.54	L	102
-1.56	L	95
-1.56	L	12
-1.56	L	80
-1.57	L	153
-1.60	L	40
-1.61	L	112
-1.62	L	83
-1.63	L	72
-1.66	L	184
-1.68	L	163

-1.69	L	54
-1.69	L	78
-1.71	L	111
-1.74	L	168
-1.76	L	41
-1.77	L	81
-1.78	L	55
-1.82	L	43
-1.84	L	44
-1.87	L	138
-1.87	L	100
-1.88	L	74
-1.88	L	186
-1.89	L	104
-1.89	L	62
-1.89	L	67
-1.89	L	61
-1.90	L	96

-1.91	L	56
-1.92	L	58
-1.92	L	53
-1.92	L	136
-1.93	L	105
-1.94	L	82
-1.94	L	18
-1.94	L	182
-1.94	L	51
-1.95	L	84
-1.95	L	134
-1.95	L	50
-1.96	L	10
-1.96	L	85
-1.96	L	71
-1.96	L	46
-1.96	L	63
-1.97	L	110

-1.97	L	113
-1.97	L	86
-1.97	L	11
-1.98	L	157
-1.98	L	68
-1.98	L	115
-1.98	L	64
-1.98	L	65
-1.98	L	117
-1.99	L	45
-1.99	L	52
-1.99	L	169
-1.99	L	118
-1.99	L	88
-1.99	L	192
-1.99	L	94
-1.99	L	114
-1.99	L	191

-1.99 L 116
-1.99 L 73

 In the foregoing matrix, the column with the title "Type" indicates the original sediment type allocation made in the field. The codes given in this column represent the following sediment types:

L	Lacustrine samples
LT	Laurentide till samples
CT	Cordilleran till samples
FS	Fluvial sand samples
A	Ash samples
I	Ice wedge samples

APPENDIX 6

PROCEDURE FOR TREND SURFACE ANALYSIS

DATA COLLECTION

The assumption made concerning the data to be used in the analysis was that summit peaks in the Elbow River basin are remnants of an earlier cycle of erosion. The data therefore represent the highest peaks within each positively closed contour in the basin. Two criteria were, however, applied before the final point value was utilized;

- 1) If two points were closer than one inch, the highest value was taken. (The data was collected on 1:50,000 topographic maps).
- 2) The summit peaks considered were selected so as to be most representative of a summit surface if they occurred on valley divides.

The Analysis

"A special case of the multiple regression problem . . . is trend surface analysis. For a map pattern of a variable Z , which is measured at a number of discrete location points, the analysis involves the regressing of this dependent variable on two independent variables U and V , which are orthogonal coordinates for the map area."

King, L. J. (1969), pp. 152.

As Krumbein and Graybill (1965) point out, the Z values are divided into two parts by the analysis. The first

part is associated with the "large scale systematic changes that extend from one map edge to the other. . .". This is the trend surface, or surface of the regression. The second part is associated with ". . . small-scale apparently nonsystemmatic fluctuations. . .". This refers to the deviations of each point from the surface, and concerns the residual values. Board (1965) refers to part one and part two as regional and local effects respectively, whilst Chorley and Haggett (1965) refer to these two parts as signal and noise. It is these two components that are used to interpret the data.

The surface is constructed such that the sum of the squared residual values is as small as possible using the basic equation of the model

$$Z_{ij} = \tau(U_i, V_j) + e_{ij} \quad (\text{King, L. J., 1969})$$

where Z is the observed value (elevation) at location (U, V) . The trend is $\tau(U_i, V_j)$ and e_{ij} is the residual.

To calculate the trend parameters a polynomial expression is used, and in this case calculated to the sixth order which involves 28 terms. The form of the polynomial is

$$Z_{ij} = \zeta_{00} + \alpha_{10}U_i + \alpha_{01}V_j + \alpha_{20}U_i^2 + \alpha_{11}U_iV_j + \alpha_{02}V_j^2 + \dots + e_{ij}$$

The computations involved when the original data is taken on a regular grid pattern is simplified by the use of orthogonal tables. In this application the points were irregularly spaced and the computations more complicated.

Whitten (1963) described methods which allow easier computation, especially for irregularly spaced control points. The computation involves a summation of each of the terms of the polynomial. This procedure is now commonly used in the programs available for trend surface analysis.

The program used (O'Leary, Lippert, and Spitz, 1966) in this study, utilized the same technique for computation of the trend as that outlined by Whitten (1963), for irregularly spaced control points (Krumbein, 1959). The following are the computations used for the error measures in the computer program.

Total variation (V)

$$V = \sum_{i=1}^N (Z_i - \bar{Z})^2$$

N is the number of observations.

$$\bar{Z} = (\sum_{i=1}^N Z_i) / N$$

Variation not explained by the surface (S)

$$S = \sum_{i=1}^N (Z_i - Z_i')^2$$

Z_i' is the calculated value.

Variation explained by the surface (E)

$$E = V - S$$

Coefficient of determination (T)

$$T = E/V$$

Coefficient of correlation (C)

$$C = T^{\frac{1}{2}}$$

Standard deviation (d)

$$D = (S/N)^{\frac{1}{2}}$$

The goodness of fit of the surface was tested using analysis of variance. The method is clearly described by King, C. A. M. (1967), and uses an 'F' test.

$$F \text{ value} = \frac{\text{Between group variance}}{\text{Within group variance}}$$

where $Q = S/N - (df-1)$ and $R = E/(df-1)$ and df is the number of expressions in the order of polynomial used to derive the surface concerned.

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